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MM&T--Ceramic Metal Substrates for Hybrid Electronics, Final Report

by A. B. Timberlake and F. E. Merti

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Westinghouse Electric Corporation
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U.S. Army Electronics Research and Development Command
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Solder leach resistance test (cont.)

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Block 19 (cont.)

Solder pull strength testing Thick Film resistor properties
Hybrid microelectronics assembly

Block 20

The results of an 18-month program are presented.

The objective was to detail the technology relevant to high volume production of thick-film hybrid electronics made with insulated-metal substrates. The technology applicable to ordnance projectile-fuze electronics was emphasized.

The program was divided into several tasks to explore the critical elements of thick-film hybrid manufacturing. First, all physical, thermal, electrical, and chemical properties of commercially available porcelain-enameled steel (PES) substrates which affect their thick-film performance were measured and analyzed. Next, the properties of numerous thick-film conductors, dielectrics, and resistors were compiled. Solderability and wire bondability of numerous conductors were evaluated. Properties of three vendors' resistor inks covering the full resistance range were characterized. Effects of firing temperature variation on thick-film properties were analyzed.

A small pilot production line was implemented using materials and processes established in the above tasks. Two batches totalling 150 units of a moderately complex hybrid fuze amplifier completed thick film fabrication with approximately 75 percent yield. Ten complete amplifiers were delivered to HDL for test.

The feasibility of building ordnance hybrids on PES substrates in large volume is discussed. Factors limiting the feasibility are identified. Areas where material development is necessary are indicated.

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PREFACE

This Final Report was prepared by the Westinghouse Electric Corporation, Defense and Electronics Center, Baltimore, Maryland, in fulfillment of Contract DAAK21-80-G-0076, "MM&T-Ceramic Metal Substrates for Hybrid Electronics". The work was sponsored by the U.S. Army Electronics Research and Development Command, Harry Diamond Laboratories, Adelphi, Maryland.

The report covers work conducted from August, 1980, through September, 1982. In addition to this report, program results were presented in a Government-Industry Demonstration held at Westinghouse DEC, Baltimore, Maryland, on September 30, 1982. Another contractual publication, "Handbook for Manufacturing Hybrid Electronics Using Insulated Metal Substrates", is being published under separate cover.

Mr. Albert Lee has served as Army Technical Monitor.

Mr. Allen B. Timberlake, Senior Manufacturing Engineer, Hybrid Manufacturing Engineering, has served as the Westinghouse Program Manager. The work was carried out under the auspices of three Westinghouse functional organizations: Hybrid Manufacturing Engineering, Louis A. Razzetti, Manager; Hybrid Electronics Facility, Michael D. Kline, Supervisory Engineer; and the Westinghouse R&D Center, Ceramic Systems Department, Dr. D.M. Mattox, Manager.

The authors wish to thank the following individuals for their contributions: Mr. James M. Kleman, Engineer, Hybrid Electronics Facility, who coordinated and oversaw most of the thick film effort performed in the Thick Film Compatibility and Guidelines Phase", Mr. Ralph Wolf, Consulting Engineer, Tech-Aid Associates, who coordinated the work performed in both the Substrate Evaluation and Thick Film Properties Measurement phases; Ms. Margaret Howard, Supervisor, Westinghouse Hybrid Prototype Laboratory, for providing technician support for wire bond and solderability sample preparation and for assembly of the Fuze Amplifiers; Mr. R.S. Holmes, Manager, Substrate Fabrication, for providing technician support for fabrication and laser-trimming Fuze Amplifier substrates; Mr. R.B. Cleverly, Senior Manufacturing Engineer, Hybrid Manufacturing Engineering, who helped plan the substrate evaluation program; Ms. Debra P. Partlow, Research Chemist, Westinghouse R&D Center, who performed

many of the substrate property measurements and data analysis and fabricated the advanced concept substrates; and to Mr. William W. Staley, Fellow Engineer, Westinghouse Advanced Packaging Groups, mechanical Design Engineering, who helped devise the Packaging Test Plan. In addition, thanks are owed to Mr. Carl Miller, Supervisory Engineer, Hybrid Manufacturing Engineering; Mr. Louis Razzetti; Manager, Manufacturing Engineering, Mr. Rick Campbell, Manager, Manufacturing MM&T Programs, and to Mr. Joseph Ansell, now associated with Watkins-Johnson Company, Rockville, Md, formerly Manager, Electronics Fabrication Branch, Harry Diamond Laboratories, for their support, guidance, and counsel. We finally wish to express our thanks to the substrate vendors, Erie Ceramics Arts, General Electric Company, and Plessey Frenchtown, both for their promptness in filling orders, and for their open and helpful discussions of substrate technology.

1. INTRODUCTION

Wide interest has been aroused in the hybrid microelectronics industry in recent years by the introduction of the insulated metal substrate (IMS) as an alternative to alumina. Papers have been published on porcelain-enameled steel (PES),[1-7*] metal coated with flame-sprayed alumina,[8,9] anodized aluminum with a copper layer epoxy-bonded to the top surface,[10,11] organic layers laminated to metal,[12,13] and copper-clad Invar (CCI).[14,15] PES and porcelain enameled copper-clad Invar are available from commercial vendors "off the shelf." In addition, a thick-film paste technology has been developed for PES and CCI.

Why is there so much interest in IMS? The following is a list of some of the more frequently quoted advantages of IMS:

- o Strength
- o Large size with high yield and low cost
- o Machinability can be made into intricate shapes
- o High heat transfer
- o Smooth surfaces
- o Adaptability to different requirements

In addition, substrates can be tailored for various applications, to achieve high heat transfer, or to match a particular thermal expansion coefficient, to cite two possibilities.

Despite many attractive features, the IMS concept has been slow in gaining acceptance, especially for complex military hardware. Several reasons for this slow acceptance have been offerred: immaturity of the technology, lack of availability of thick-film inks to perform various functions, and inconsistency of properties of materials. In short, the industry has failed to establish the manufacturing controls and processes for substrates, film materials, and assembly techniques suitable for high-volume production. Consequently, the promise of IMS has not been realized.

1.1 BACKGROUND

The potential advantages of IMS were discussed above. Ordnance electronic circuitry used by the U.S. Army to control the operation of ordnance devices must be able to survive in an especially severe environment. Ordnance requirements are listed below:

- o Shock survivability
- o Firing - 30,000 + g's
- o Spin - 20,000 rpm
- o Impact - 5,000 + g's (function of target density)
- o Large volume producibility
- o Low cost

* See Literature Cited, pp 117-118

- o Stability over long periods
- o Shielding against radio frequency interference (RFI)

These circuits must function after severe and diverse mechanical shock resulting from gun firing, spin, and impact, as shown. Stresses are especially severe during firing, when shock levels may exceed 30,000 g for several milliseconds. Alumina substrates survive such stresses only when they are selected for flatness and supported by expensively machined steel assemblies. Potentially, IMS has the strength to survive these stresses without special selection or costly support assemblies. Thus a substantial reduction in total system cost is possible with the use of IMS.

In addition to lower systems cost and improved reliability, the high-volume production of ordnance hybrids requires that the manufactured devices maintain low costs and high yields for all phases of production. This requirement must be maintained with any new substrate concept under consideration. Close compatibility with existing manufacturing processes (e.g., circuit definition, component attachment, and packaging) is essential to meet this requirement. The IMS technology can be implemented into a standard thick-film line by altering existing hardware within its normal range of adjustment. Therefore, conversion of a hybrid design from alumina substrates to IMS should be feasible with a minimum impact on facilities and a relatively short period of learning and adjustment.

The attributes of the IMS make it attractive for ordnance applications. Other potential advantages to this type of substrate could be desirable in other applications, such as high yields with large sizes, low cost, machinability, high heat transfer, and smooth surfaces. Large sizes, needed for advanced very-large-scale integration hybrids, are achievable without the risk of high breakage losses which limit the maximum size considered practical for alumina. It is practical to achieve intricate machinable shapes, with bent surfaces and built-in construction features such as mounting holes and tabs.[16] Also, by proper choice of materials, heat transfer from circuit elements can be increased (compared to that achieved with ceramic) to improve circuit performance and reliability. When the insulating material is porcelain, the smooth surface can improve thick-film screen printing characteristics.

It should be emphasized that the properties cited above are considered "potential" and have not necessarily been partially or totally realized on mass-produced IMS.

1.2 PROGRAM OBJECTIVE

From the preceding information it is evident that sizeable benefits could accrue both to the U.S. Army and to the electronics industry in general if the potential of IMS can be realized. For this to occur, the methods and technology for high-volume production of thick-film hybrids have to be established, and the manufacturing methods, processes, and controls relevant to these unique substrates have to be clearly detailed.

The U.S. Army Electronics Research and Development Command, through Harry Diamond Laboratories, has sponsored a Manufacturing Technology Program,

"Ceramic Metal Substrates for Hybrid Electronics," with Westinghouse Electric Corporation. The overall objective of this program is to establish and detail the methods and technology required for production of ordnance hybrids, using insulated metal substrates.

This report describes the work done and the results obtained by Westinghouse in pursuance of the objective.

2. PROGRAM ORGANIZATION

In order to achieve the objectives, the program was divided into functional tasks which interacted as shown in figure 1. The elements which make up a hybrid circuit were evaluated individually, and the results applied to the manufacture of a hybrid cirucit now used in large quantities by the Army.

As can be seen in figure 1, the beginning phase of the program deals with substrates. Various IMS concepts, including PES, ceramic sprayed on metal, and anodized aluminum, were chosen for more intensive investigation. A test plan for obtaining information needed for using these substrates in high-volume production was prepared and carried out.

The second phase of the program was concerned with the characteristics of thick films processed on the IMS selected for evaluation in the first phase. The objective was to establish design guidelines for thick film on this kind of substrate. Minimum line widths and spacings, limitations on printed resistor size, solder pad area and thickness requirements, and the overall compatibility of thick-film technology with the particular IMS selected were determined.

Packaging was reviewed in another phase of the program. Those elements of construction of a hybrid necessary to permit it to function and survive in fabrication, test, storage, and use were investigated on hybrids made using the IMS PES. New packaging concepts made possible by the unique properties of the IMS were also considered.

The results were used in the fabrication of a hybrid circuit selected by the Army. Ten complete operating circuits of a design representative both in size and complexity were built. Estimates were made of cost, yields, and amenability of the materials, processes, and design for production rates of 5000 units per week.

The technology and lessons learned in the course of this evaluation were presented to the public in three media: an industry demonstration at the Westinghouse Defense and Electronics Center, Baltimore, Maryland, at the end of the program in September of 1982; this document, the final report; and a handbook detailing guidelines for the selection and specification of materials, processes, and designs.

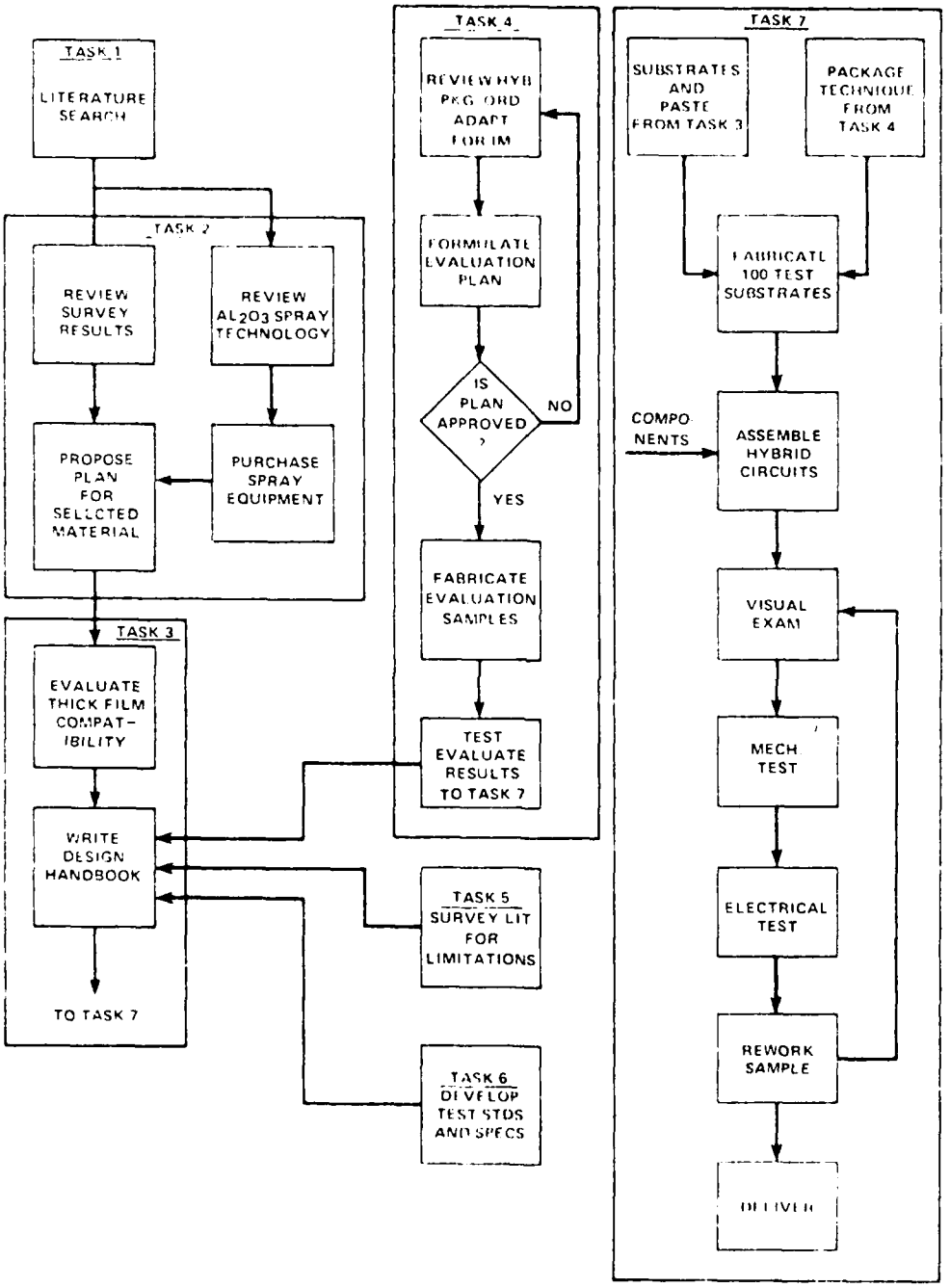

Figure 1. Ceramic Insulated Metal Substrate Program

3. SUBSTRATES

3.1 SELECTION OF SUBSTRATE TECHNOLOGY

The first tasks performed in the program were concerned with the selection of a substrate structure for evaluation and with the evaluation itself.

All the substrate structures described were technically attractive for reasons discussed earlier. Therefore, a limited effort was directed toward evaluation of an IMS other than PES. Since substrates of this kind were not production items, the results were regarded as preliminary and tentative.

3.2 TEST PLAN

To validate the substrate selection process, a plan for substrate evaluation was devised. The purpose of this plan was both to evaluate and to describe as quantitatively as possible the substrates that are available from commercial vendors for fabrication of thick-film hybrids. Characteristics which affect the high-volume producibility of thick-film hybrids were highlighted. Not only mean values, but ranges and deviations of the various properties were recorded. The statistical significance of deviations from the mean was analyzed, when possible.

PES substrates were investigated in this program to determine their acceptability for use in thick-film hybrids. Thick film technology based on alumina substrates has provided a wealth of knowledge about the properties a substrate must have in order to be acceptable for thick film. To a lesser extent, a thick film technology based on PES has grown and knowledge exists of the properties this type of substrate must have to be used successfully in hybrid production. In addition, many undesirable characteristics which may be found in substrates of both types are known.

The tests planned for the evaluation were selected using these areas of experience as a guide. In addition, manufacturers' data sheets and ISHM Specification, SP009 "Hybrid Microelectronics Specification Guidelines" for substrates, provided information on the properties to be tested and the methods of measurement to be used. Most tests were performed according to ANSI procedures.

3.2.1 Test Plan Details

Table 1 lists the tests that were performed, the test method, and the size of the test sample from the first lot received from each vendor.

3.2.2 Test Sample Vendors and Make-Up

It is appropriate, in discussing the sources of the substrates used for the evaluation, to review events in the substrate market which have occurred since the program began in September, 1980.

In early 1980, there were three major suppliers of PES substrates: Alpha Metals, Newark, New Jersey; Erie Ceramic Arts, Erie, Pennsylvania; and General Electric Corporation, Cleveland, Ohio. Alpha withdrew from the business in mid-1980, leaving Erie and GE.

Late in 1980, the Frenchtown Porcelain Division of Plessey, Ltd, entered the market with a line of porcelain-enameled metal substrates, the metal cores of which could be conventional porcelainized steel, stainless steel, or steel-clad Invar. (Invar is an iron-nickel alloy with a thermal expansion coefficient of almost 0.) In 1981, Plessey sold this operation to a group of private investors, and the company was renamed "Frenchtown American."

In mid-1980 RCA Corporation scientists at the David Sarnoff Research Center, Princeton, New Jersey, announced the development of a PES substrate and system of copper-based thick film inks formulated expressly for their substrates.[17-20] A key feature of these substrates was their ability to be fired many times at temperatures in excess of 900°C. In addition, they featured low sodium content, good edge coverage with small menisci, and were free of pin-holes.

TABLE 1 SUBSTRATE TESTING

Property	Method	Sample from each lot
1) Dimensions	Calibers	15
2) Surface finish	ANSI B 46.1	15
3) Flatness/camber	Flat plate and dial gage	15
4) Edge meniscus	Profilometer	15
5) Surface resistivity	ASTM D257	2
6) Dielectric constant, dissipation factor, and dielectric strength	ASTM E228	4
7) Coefficient of thermal expansion	ASTM E228 C372	1
8) Thermal shock	MIL-STD-883 Method 1011.2, Cond. B.	4
9) Thermal conductivity	ASTM C408	1
10) Softening temperature	ASTM C372	6
11) Alkali content	Chemical analysis	
12) Area scans for elements listed: sodium, Ca, Si, Al, Fe, Ni	Microprobe	1

Although the RCA-developed substrates were excellent candidates for evaluation, they were not available for purchase. Rather, RCA chose to sell licenses for manufacture of the entire system, including substrates, enamel, and inks. It was not possible within the constraints of time and budget to enter into such an arrangement, and the substrates were not included in the evaluation.

During 1981 engineers at RCA-Moorestown, N.J., working in conjunction with scientists at Erie Ceramic Arts, Ferro Corporation, and Texas Instrument Specialty Metals Division in Attleborough, Massachussetts, developed a new substrate[21]. The metal core was copper-clad Invar, and the insulating coating was "El-Por 2," a new "electronic porcelain" developed to be used with this metal, or with steel. Although this type of substrate was available in the open market, it arrived too late to be given the full investigation accorded the earlier types.

3.2.2.1 Porcelain Enameled Substrates

The substrates for evaluation were purchased from the following vendors:

Erie Ceramic Arts (ECA)
Erie, Pennsylvania

General Electric Corporation (GE)
Cleveland Ohio

Plessey Frenchtown (PL)
Frenchtown, New Jersey

Substrates as described in table 2 were ordered for evaluation, from the three vendors. Note that the ECA and GE 1 x 2 in. substrates were ordered in three shipments, i.e., from three manufacturing lots. This sample composition was used to provide an indication of lot-to-lot consistency of materials.

The PL materials were included although PL at the time was somewhat limited in capacity and facilities. The performance of different core metals, as supplied-by PL, was of interest, as was the performance of sprayed versus electrophoretically deposited coatings.

TABLE 2 SUBSTRATES FOR EVALUATION

Vendor	Size (in.)	Base metal	Treatment	Deposition	Quantity
Erie Ceramic Arts	1 x 2	Low-carbon (LC) steel	Etch	Electro phoretic (EP), both sides	150 in 3 shipments
Erie Ceramic Arts	2 x 2	LC steel	None	EP-both sides	10
General Electric	1 x 2	LC steel	None	EP-both sides	150 in 3 shipments
Plessey Frenchtown	1 x 2 1/2	LC steel	Edges rounded	Spray-one side	50
Plessey	1 x 2	303 stainless steel	Edges rounded	Spray-one side	50
Plessey	1 x 2	Steel Invar laminate	Edges rounded	Spray-one side	10
Plessey	1 x 2	LC steel	Edges rounded	Spray-one side	10
Westinghouse R&D Center	1 x 2	Alloy 42	De-carburized	Plasma spray 95% alumina - 5% Yttria	25

3.2.2.2 Ceramic Coated Substrates

A small number of substrates made at Westinghouse Research Labs by plasma spraying ceramic on metal were obtained and evaluated. Alloy 42 was used as the metal core because it meets thick film processing requirements, possesses good thermal and mechanical properties, and is known to be coatable with sprayed alumina or other high-grade ceramics.

3.3 TEST RESULTS

3.3.1 Surface and Edge Contour

The dimensional and surface finish properties of PES substrates from each of the three selected vendors were examined during this period. To measure flatness, profilometer scans were made of 15 substrates from each lot from ECA and GE.

A typical trace, from which meniscus height and width were taken, is shown in figure 2.

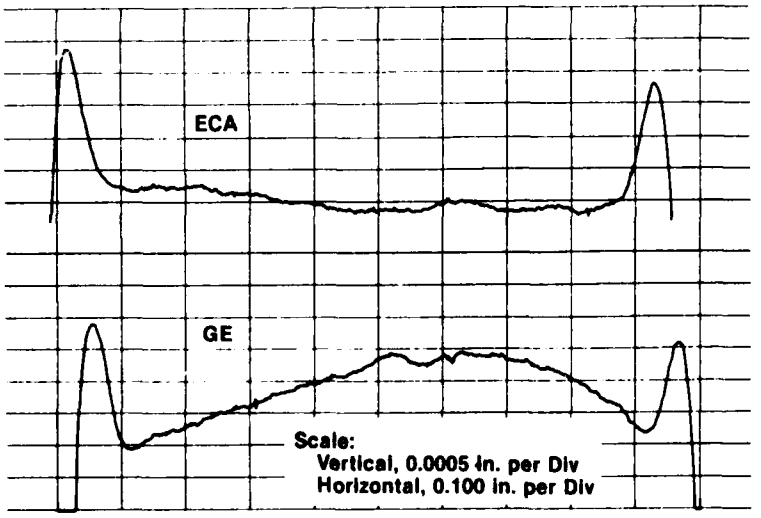

Figure 2. Typical profilometer traces of ECA (top) and GE (lower) substrates.

The substrates were also measured with a surface plate and dial indicator to determine flatness, camber, and edge meniscus. Length, width and overall thickness were measured using calipers.

Results of the edge meniscus measurements are shown in table 3 for the ECA and GE substrates. Histograms for these data are shown in figure 3 and 4. The PL substrates, being coated only on one side, did not lend themselves to edge meniscus measurements. It can be seen that the meniscuses for most substrates extended almost 0.100 in. in from each edge. Meniscus heights ranged from 1 to 3 mils.

The dimensional data for the ECA and GE substrates are summarized in table 4. The GE substrates are very close to their nominal 1.0 by 2.0 in., whereas the ECA substrates are consistently 0.007 to 0.009 inches oversize. The column headed "Thickness, center" presents the data for the substrate height. The difference in values between these columns is a measure of the substrate deviation from flatness. This quantity may be a significant indicator of substrate usefulness in certain applications.

Substrates from each vendor were observed to have certain characteristic dimensional irregularities. The GE substrates had a small bow across the width. The ECA substrates had a buildup of porcelain at the corners that was greater than the meniscus along the sides. The PL substrates were bowed and many were extremely wavy.

Samples of substrates from each vendor were inspected visually for pin holes and other surface defects. No pin holes were observed under 50X, 100X, or 400X magnification.

It should be noted that the meniscus, bow, and waviness of PES substrates make them very difficult to describe quantitatively. Existing industry and ASTM documents provide virtually no guidance. One appropriate project would be to identify geometrical characteristics peculiar to PES substrates which are significant to a thick film manufacturer.

TABLE 3. EDGE MENISCUS MEASUREMENTS

Lot	Width (mils)			Height (mils)		
	Mean	Std dev	Range	Mean	Std dev	Range
General Electric						
Lot 1	77	10	33	1.04	0.68	1.84
Lot 2	96	10	34	2.24	0.24	0.82
Lot 3	92	12	44	1.97	0.34	1.08
Erie Ceramic Arts						
Lot 1	95	16	45	1.73	0.34	1.04
Lot 2	90	14	56	1.80	0.43	1.20
Lot 3	98	11	37	1.77	0.25	0.84

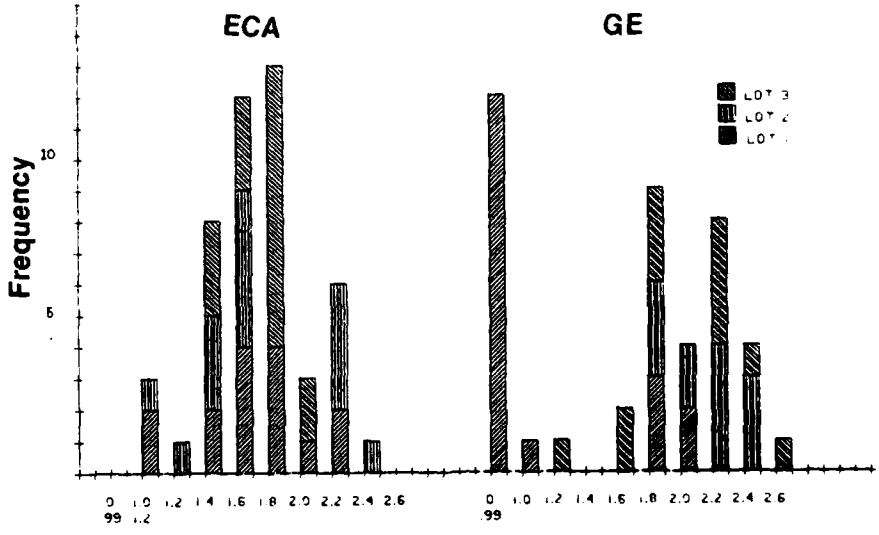

Figure 3. Distribution of Meniscus Heights (10^{-3} in.)

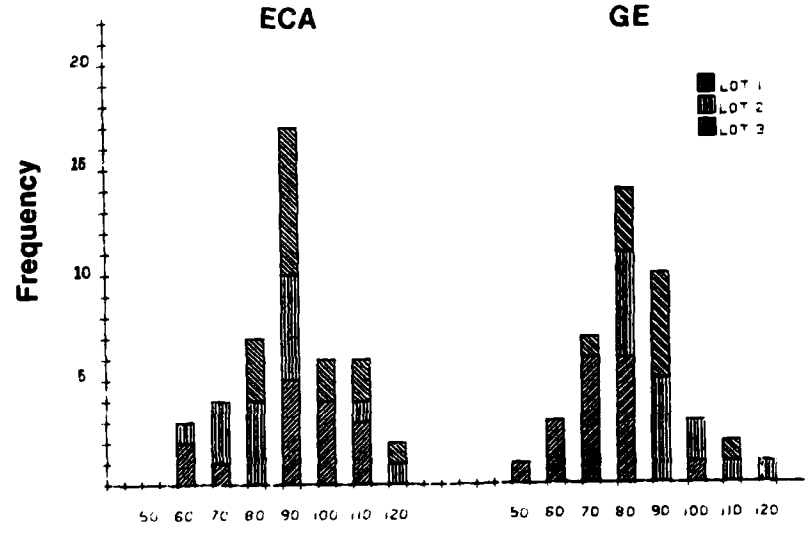

Figure 4. Distribution of Meniscus Widths (10^{-3} in.)

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TABLE 4. DIMENSIONAL ANALYSIS

Lot	Length, (in.)			Width, (in.)			Thickness, center (in.)			Thickness, center Overall (in)		
	Mean	Std dev	Range	Mean	Std dev	Range	Mean	Std dev	Range	Mean	Std dev	Range
General Electric												
Lot 1	1.999	0.001	0.003	0.999	0.001	0.003	38.4	0.3	0.6	42.8	1.3	4.1
Lot 2	2.001	0.001	0.003	1.001	0.001	0.002	39.9	0.4	1.2	44.0	1.3	4.4
Lot 3	2.001	0.001	0.003	1.000	0.001	0.003	39.0	0.8	3.5	42.7	1.3	3.9
Eric Ceramic Arts												
Lot 1	2.008	0.001	0.002	1.008	0.001	0.002	43.4	0.9	1.8	48.5	1.8	6.4
Lot 2	2.009	0.001	0.002	1.008	0.001	0.002	41.2	0.2	0.6	46.4	2.4	6.7
Lot 3	2.008	0.001	0.002	1.007	0.001	0.003	41.7	0.6	1.2	44.9	0.8	2.1

3.3.2 Thermal Properties

3.3.2.1 Coefficient of Thermal Expansion

The thermal expansion coefficients of a sample from each of the three lots from each vendor were measured using a quartz dilatometer. One inch squares cut from the 1 x 2 in. substrates were heated in a controlled temperature furnace from room temperature to 400°C. One end of the substrate under test was fixed in position, and the other end was free to move as the substrate expanded. The free end was in contact with a quartz rod, which in turn contacted a sensitive length indicator. The change in length of the substrate could thus be recorded as a function of temperature.

The thermal expansion coefficient, α, is usually given as a linear approximation over a particular temperature range. (The incremental expansion coefficient at a single temperature point may vary considerably from this value.) The linear approximation is calculated using equation (1),

$$\alpha = \frac{L_t - L_o}{L_o(T - T_o)}, \qquad (1)$$

where

L_t = length of the specimen at elevated temperature T, and

L_o = length of the specimen at lower temperature T_o

Results are given in table 5. As expected, the steel core dominates the value. Lot-to-lot consistency was quite good.

TABLE 5. THERMAL EXPANSION COEFFICIENTS, PORCELAIN-ENAMELED SUBSTRATES

Temperature range	10^{-6} in./in./°C		
	Erie Ceramic Arts		
°C	Lot 1	Lot 2	Lot 3
40-100	16.0	15.3	16.1
100-200	14.0	12.6	13.0
200-300	12.3	13.8	11.8
40-300	13.8	13.7	13.3
	General Electric		
	Lot 1	Lot 2	Lot 3
40-100	16.2	16.7	16.8
100-200	12.6	13.2	14.5
200-300	12.6	13.2	13.8
40-300	13.5	14.0	14.8
	Plessey, Frenchtown		
	Lot 1	Lot 2*	Lot 3**
40-100	14.2	20.5	9.5
100-200	14.6	18.6	6.0
200-300	15.1	16.7	10.1
40-300	14.7	18.3	8.4
	3M AlSiMag 614***		
25-300	6.4		
	Steel		
20-300	13-15		

* Porcelain enameled stainless steel
** Porcelain enameled steel-Invar-steel laminate
*** 3M Company, bulletin number 757, Properties of Al Si Mag Ceramics. "Al Si Mag" is a registered trademark of 3M Company.

3.3.2.2 Softening Temperature

For the porcelain softening point measurement, one sample from each lot was cut into a number of pieces approximately 1/4 x 1/4 in. The pieces of each sample were stacked separately and placed in a furnace at approximately 800°C for 3 minutes, in order to fuse the stack. This was done to provide a sample approximately 1 in. long, since this is the minimum sample length the dilatometer can accept, and since it was necessary to make this measurement parallel to the porcelain thickness. The thermal expansion measurement procedure was then carried out until a temperature was reached where a negative slope could be observed in the thermal expansion curve. The temperature at which zero slope occurred was taken as the porcelain softening point. These values are given in table 6. The measurement was repeated for PL lots 1 and 2 to provide information on the reproducibility of these results.

TABLE 6. PORCELAIN SOFTENING TEMPERATURE

	Softening Temperature (°C)		
Lot	ECA	GE	PL
1	590	580	570-575
2	590	565	565-580
3	600	570	565

These data indicate that all of the enamels tested could soften at the temperature used to fire many pastes formulated for PES. Additional tests would be required to determine whether the viscosity would allow "swimming" of the paste pattern.

3.3.2.3 Thermal Conductivity

The "apparent" thermal conductivity at 50°C was measured on circular specimens 3/4 in. in diameter cut from one substrate from each lot.

The thermal conductivity was measured by Dynatech R/D Company, Cambridge, MA, using the Colora Thermoconductometer. The sample was placed between polished silver plates which could be kept at the given boiling points of two liquids by a constant supply of heat to the higher boiling point liquid. When steady equilibrium was attained, the lower boiling point liquid vaporized at a constant rate and was condensed and collected in a measuring vehicle. The time for a given volume to distill was measured.

The thermal conductivity, k, was calculated from equation (2), as follows:

$$k = \frac{q}{\Delta T} \frac{1}{A} \qquad (2)$$

where q =

rate of heat transfer from one liquid to the other, based on mass of liquid vaporized, heat of vaporization, and time elapsed,

ΔT = temperature difference between two liquids

l = specimen thickness, and

A = specimen cross-sectional area.

The results for the samples tested are shown in table 7. Values are also shown for alumina, steel, and glass.

An effective thermal conductivity, k_{eff}, for a coated specimen may be calculated from the formula

$$k_{eff} = \frac{k_1 k_2 (l_1 + l_2)}{k_2 l_1 + k_1 l_2} \tag{3}$$

where k_{eff} =
thermal conductivity of a homogenious specimen of the same total thickness, cross-sectional area, and thermal conductance as the test specimen.

k_1, k_2 = thermal conductivities of core metal and coating, respectively, and

l_1, l_2 = thicknesses of core metal and total coating, respectively.

For all ECA, GE, and PL Lot 1 specimens, the following values were used:

$$k_1 = 0.47 \ \frac{\text{watt}}{\text{cm deg C}} \ \text{(Steel)}$$

$$k_2 = 0.014 \ \frac{\text{watt}}{\text{cm deg C}} \ \text{(Glass)}$$

For Plessey Lot 2, K_1 was $0.16 \ \frac{w}{\text{cm } ^oC}$

Values of k_{eff} calculated from equation (3) for all substrate lots are also shown in table 7. Thickness of the steel cores and porcelain coatings were measured directly. In all cases, calculated values were higher than measured values. Measured values of k_{eff} were approximately 75 percent of calculated values for the GE substrates and 90 percent for the ECA. The PL lot 1 sample could not be measured because of warpage, while the lot 2 sample was measured to be less than half its theoretical value.

TABLE 7. APPARENT THERMAL CONDUCTIVITY OF A PORCELAINIZED METAL SUBSTRATE AT 40°C

Sample	Porcelain thickness cm (in)	Metal core thickness cm (in)	Apparent thermal conductivity W/cm deg (BTU in/hr ft2 deg F) Measured	Calculated
ECA 1	.0269 (.0106)	.081 (.0321)	0.048 (33.3)	0.053 (36.8)
ECA 2	.0276 (.0089)	.081 (.0321)	0.050 (34.7)	0.058 (40.2)
ECA 3	.0234 (.0092)	.081 (.0321)	0.052 (36.1)	0.057 (39.5)
GE 1	.0312 (.0123)	.064 (.026)	0.030 (20.8)	0.041 (28.4)
GE 2	.0353 (.0139)	.064 (.026)	0.029 (20.1)	0.038 (26.4)
GE 3	.0325 (.0128)	.064 (.026)	0.030 (20.8)	0.040 (27.8)
PL 1	.0229 (0090)	.076 (.030)	-	0.055 (38.2)
PL 2	.0114 (0045)	.083 (.0325)	0.027 (18.7)	0.071 (49.3)
Low Carbon Steel	-	-	0.47 (324)	-
96% alumina	-	-	0.276 (191)	
Porcelain-enameled copper (PEC)	(.010)	(.030)		0.055 (38.2)
PEC	(.005)	(.030)		0.096 (66.6)

There are at least two possible causes for the discrepancy between measured and theoretical values seen here. First, the value of 0.014 for porcelain could be in error. In that case the discrepancy for GE substrates would be greater than that for ECA since the porcelain on the GE substrates constitute a larger fraction of the total thickness than the porcelain on the ECA. Second, substrate warpage and bow could prevent good thermal contact to the specimen being measured. Again, this factor would be more apparent on the GE substrates, which had a characteristic bow, as seen in figure 2.

One final point should be made in discussing these data. Effective thermal conductivity is dominated by the porcelain. The GE substrates, although thinner than the ECA, were much lower in thermal conductivity, due to their thicker porcelain coatings. Even the PL lot 2 substrates, with a metal core of much lower conductance than the others, had a higher theoretical effective conductivity because of its thinner coating. The values of k_{eff} for a

porcelain-enameled copper, where the copper is 0.030 in. thick and enamel thickness 0.010 is in. are close to those of PES. Lowering the porcelain thickness to 0.005 in. increases k_{eff} by almost 100 percent. Thus, if high thermal conductance is a requirement, porcelain must be as thin as other considerations will permit.

3.3.3 Electrical Properties

3.3.3.1 Surface Resistivity

Surface resistivity, conventionally given in ohms per square, was calculated from the measured value of surface resistance, since the former may be defined as the surface resistance over an area of 1 cm^2. Resistance values were obtained using a Hewlett-Packard High Resistance Meter, Model #4329A. Electrical contacts of silver paste were applied on the surface of each sample in a controlled configuration through the use of disposable adhesive paper masks punched with a a steel die. The test pattern consisted of two parallel rectangles of silver paste 2 mm x 1.5 cm, centered 1.5 cm apart. The resistance was thus measured over an area 1.3 x 12.5 cm, and results were normalized to an area of cm^2. Before application of these contacts, each sample was cleaned with dry ethanol; organics in the applied paste were driven off by heating at 50°C for approximately 1 hour. Cleaning between the contacts was repeated immediately before taking the reading. During the measurement, the sample was shielded from adjacent fields by being surrounded with a grounded copper mesh cage. Five samples from each lot were measured, and the results are given in table 8.

TABLE 8. Surface Resistivity of PES Substrates (measured at 50 Vdc)

		Surface Resistivity 10^{11} Ohm/sq		
Vendor	Lot	Maximum	Mean	Minimum
ECA	1	2.9	2.1 ± 0.5	1.5
	2	2.2	1.8 ± 0.3	1.5
	3	1.6	1.5 ± 0.1	1.3
GE	1	2.0	1.8 ± 0.2	1.6
	2	2.0	1.8 ± 0.2	1.6
	3	1.9	1.6 ± 0.2	1.3
PL	1	1.7	1.6 ± 0.1	1.5
	2	2.8	1.9 ± 0.5	1.6
	3	2.1	1.8 ± 0.2	1.6

3.3.3.2 Dissipation Factor and Dielectric Constant

To prepare the samples for these measurements, all edges were removed by grinding with abrasive (SiC) paper. This served to eliminate variations in thickness due to the meniscus as well as to separate the two flat enamel

layers from each other. All surfaces were then cleaned with dry ethanol, and silver paste was applied over the enamel surfaces, taking care not to allow the paste to touch the now-exposed metal edge. Note that the PL samples were only enameled on one side, thus requiring only one silver coating. Coated samples were dried at 50 °C to drive off organics in the paste. Capacitance, dissipation factor, and conductance were measured using a Hewlett-Packard automatic capacitance bridge, model 4270A, equipped with a 16011A test fixture. The sample was again shielded from adjacent fields during the measurements by a grounded copper mesh cage. The above-mentioned parameters were measured at frequencies ranging from 1 kHz to 1 MHz. Dielectric constant was calculated from the capacitance using the expression

$$\epsilon_r = \frac{dC}{2\,\epsilon_o A}, \tag{4}$$

where

d = thickness of single layer of enamel (meters),

C = measured capacitance (farads),

A = area of silver plates (meters squared),

ϵ_o = dielectric constant of free space (8.9×10^{-12} $C^2/N\text{-}m^2$).

It is implicit in equation (4) that the samples are enameled equally on both sides, and that the capacitance of the enamel on one side is equal to that of the enamel on the opposite side. The thickness of one layer of enamel was calculated by measuring the total sample thickness with a micrometer, substracting the metal thickness, and, where the sample was enameled on both sides, dividing by 2. Thus, this practice assumes that the enamel layer thicknesses on each side of a given sample were also comparable. The metal thickness had been determined to be 30 mils for ECA and PL samples, and 25 mils for GE samples. This had been found by removing the enamel from a few samples.

Two substrates from each manufacturer's lots were measured at frequencies of 1 kHz, 10 kHz, 100 kHz, and 1 MHz. No frequency dependence was observed in the results, except for the dissipation factors of the PL materials. Likewise, the pairs of samples in each group were essentially identical, except for the PL materials.

The results obtained at a measurement frequency of 1 kHz are presented in table 9. The ECA and GE data are averages obtained on the two samples in each group. Values measured on each Plessey substrate are presented.

The measurements indicate good lot-to-lot consistency. The values of dielectric constant are in the range given for porcelains in the Handbook of Chemistry and Physics, 6.0 to 8.0.

TABLE 9. DIELECTRIC PROPERTIES OF PES SUBSTRATES AT A MEASUREMENT FREQUENCY OF, 1 kHz

Vendor-lot	Measured capacitance (pf)	Dielectric constant	Dissipation factor
ECA-1	340	7.8	0.0031
ECA-2	490	7.8	0.0037
ECA-3	487	8.3	0.0033
GE-1	374	7.8	0.0034
GE-2	340	7.3	0.0034
GE-3	346	7.8	0.0034
PL-1	442	7.9	0.0037
	497	6.9	0.0049
PL-2	521	9.4	0.0081
	464	8.8	0.0070
PL-3	481	4.3	0.0052
PL-3	324	4.1	0.0047

3.3.3.3 Dielectric Strength

Following the surface resistance measurement, one sample from each lot was used for dielectric strength measurements. One of the silver rectangles was used as one contact, and the circuit was completed by contacting the metal base. A dc voltage, applied between the silver and the metal base, was increased at a rate of 1 kV/s and the breakdown voltage was recorded. These tests (like those described above) were done at room temperature. During the measurement, the sample was immersed in DC-200 fluid to prevent current leakage around the edges. Breakdown voltages were divided by the enamel thickness, determined as stated above, and dielectric strengths, in volts per centimeter, are given in table 10.

TABLE 10. DIELECTRIC BREAKDOWN STRENGTH (VOLTAGE INCREASE RATE, 1 kV/s)

Vendor-lot	Dielectric strength (10^5 V/cm)
ECA-1	4.3
ECA-2	4.0
ECA-3	4.3
GE-1	4.1
GE-2	3.3
GE-3	3.8
PL-1	2.8
PL-2	3.2
PL-3	2.6

3.3.4 Alkali Ion Content

The alkali ion content of the enamels is of interest, because alkalis are detrimental to the electrical properties of substrates, promoting "brown plaque" and silver migration. Gravimetric methods (wet chemistry) were used to determine lithum, sodium, and potassium content for one sample from each lot. Results, expressed in weight percent, are represented in table 11.

It can be seen that the ECA and GE substrates are similar in alkali ion content, except that the sodium content of ECA Lot 3 is more than twice that of the other lots. The PL substrates, on the other hand, are much lower in sodium than Erie or GE substrates, but much higher in lithium and potassium. All vendors products showed good lot-to-lot consistency.

The variations noted could not be correlated with surface resistivity, dielectric constant, dissipation factor, breakdown voltage, or softening temperature. Time did not permit an investigation of long-term aging effects which might be attributable to these materials.

TABLE 11. ALKALI CONCENTRATIONS IN COMMERCIALLY AVAILABLE PORCELAINS USED AS ENAMELS ON METAL SUBSTRATES

Vendor-lot	Concentration of indicated element, (Wt %)		
	Li	Na	K
ECA-1	0.13	2.4	5.4
ECA-2	0.12	2.7	6.0
ECA-3	0.13	5.8	5.4
GE-1	0.10	2.4	6.5
GE-2	0.09	2.7	7.0
GE-3	0.09	2.5	5.8
PL-1	0.26	0.21	10.5
PL-2	0.25	0.27	14.8
PL-3	0.21	0.28	9.2

3.3.5 Elemental Distribution by Electron Microprobe Analysis

Area scans of various elements were done by electron microprobe analysis to show the distribution of various elements through the enamel (homogeneity) and to determine the extent of diffusion of material from Ni, Fe, Al, and Si. Results are presented in figures 5 through 16. It should be noted that the concentrations of two different elements cannot be compared to each other, because different counting rates were used for each element. However, the concentration of a given element can be compared between any two samples. In all cases, the enamel/metal interface is at the bottom of the micrograph, and

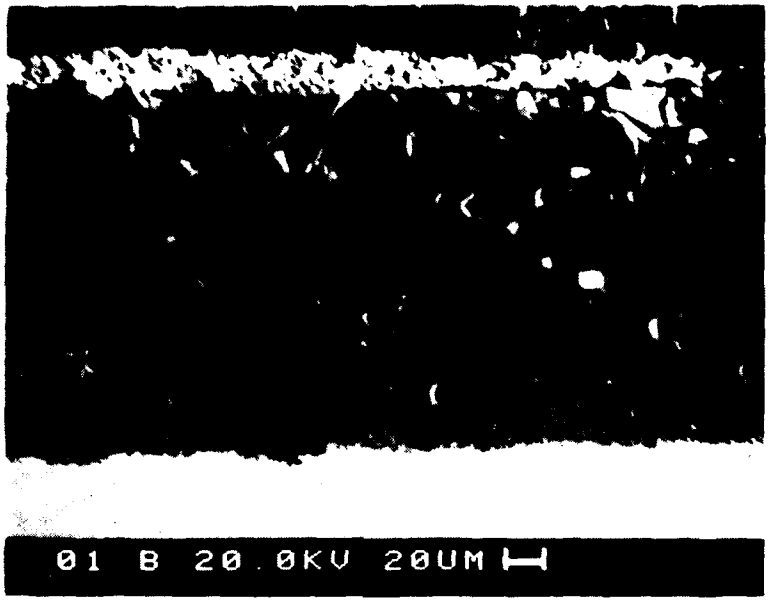


Figure 5. Backscattered electron micrograph of ECA lot 1 sample.

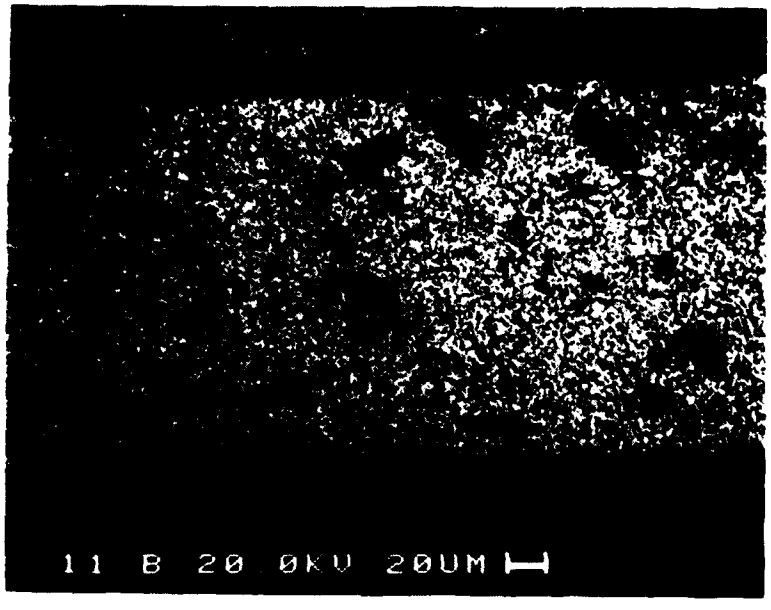


Figure 6. Electron microprobe area scan showing distribution of Na in ECA lot 1 sample.

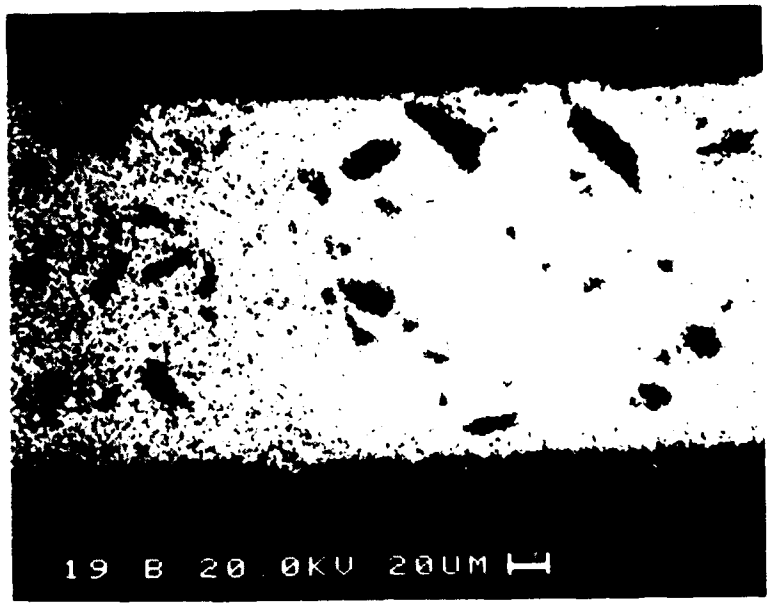


Figure 7. Electron microprobe area scan showing distribution of K in ECA lot 1 sample.

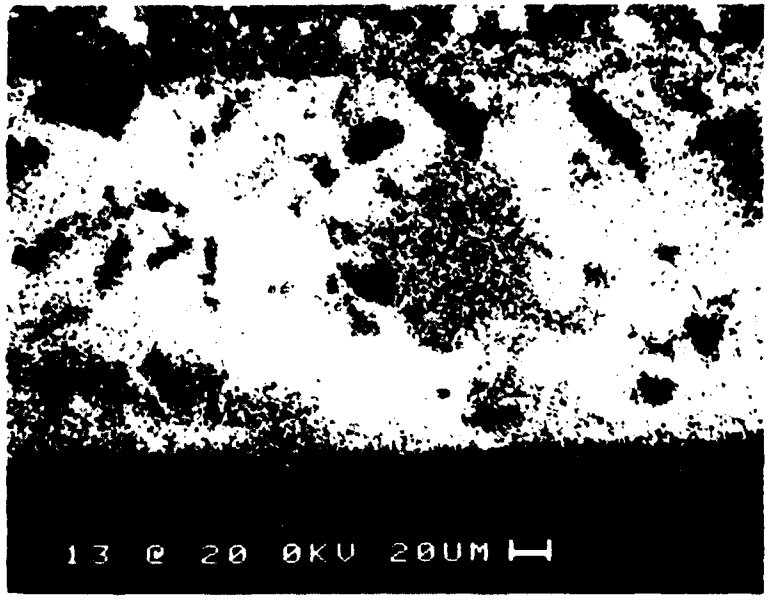


Figure 8. Electron microprobe area scan showing distribution of Al in ECA lot 1 sample.

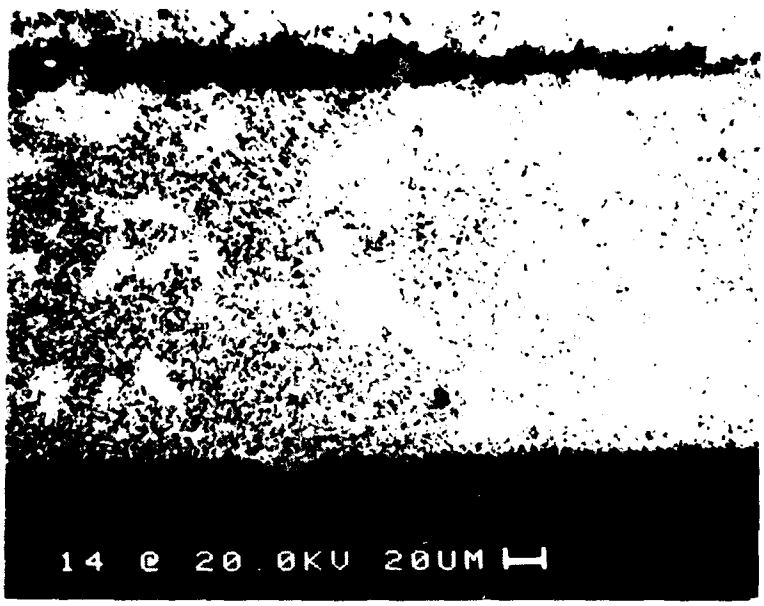


Figure 9. Electron microprobe area scan showing distribution of Si in ECA lot 1 sample.

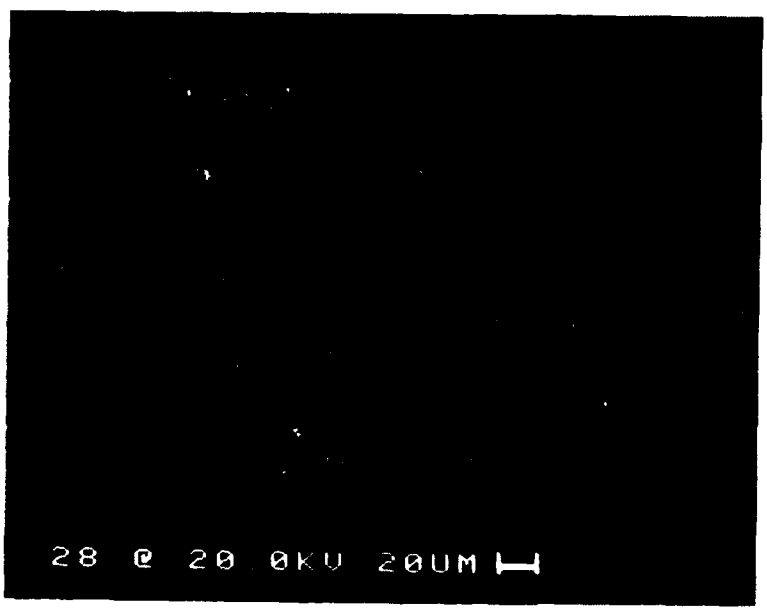


Figure 10. Electron microprobe area scan showing distribution of Ni in ECA lot 1 sample.

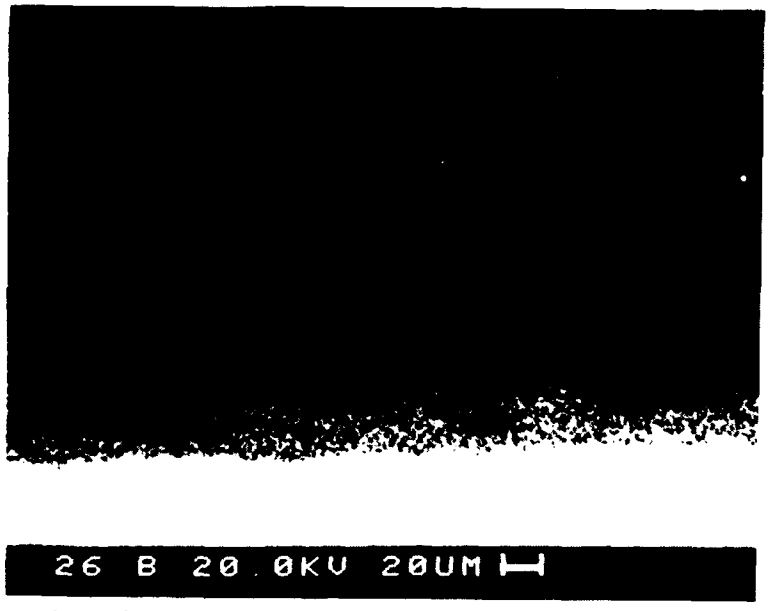


Figure 11. Electron microprobe area scan showing distribution of Fe in ECA lot 1 sample.

Figure 12. Backscattered electron micrograph of GE lot 1 sample.

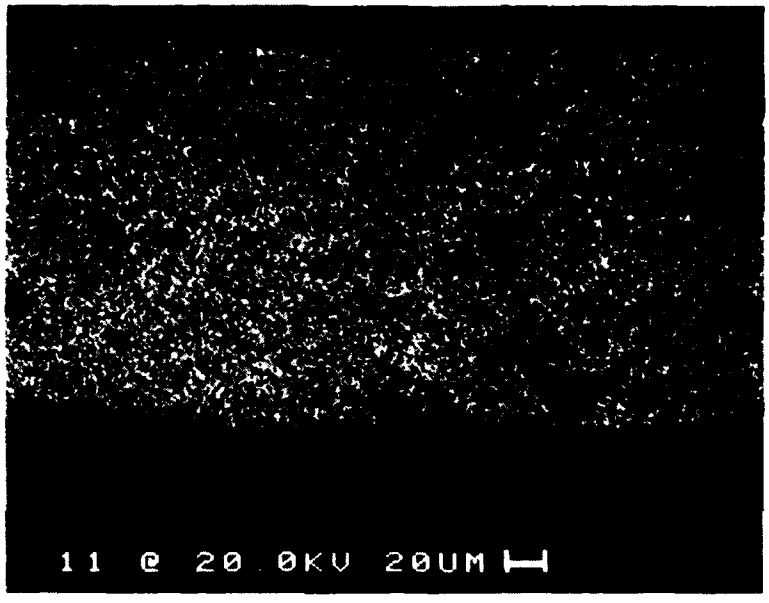


Figure 13. Electron microprobe area scan showing distribution of Na in GE lot 1 sample.

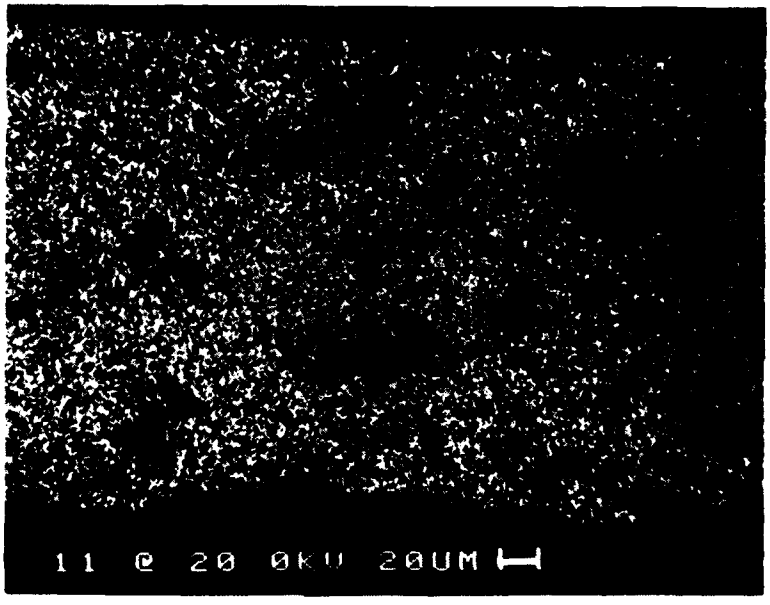


Figure 14. Electron microprobe area scan showing distribution of Na in GE lot 2 sample.

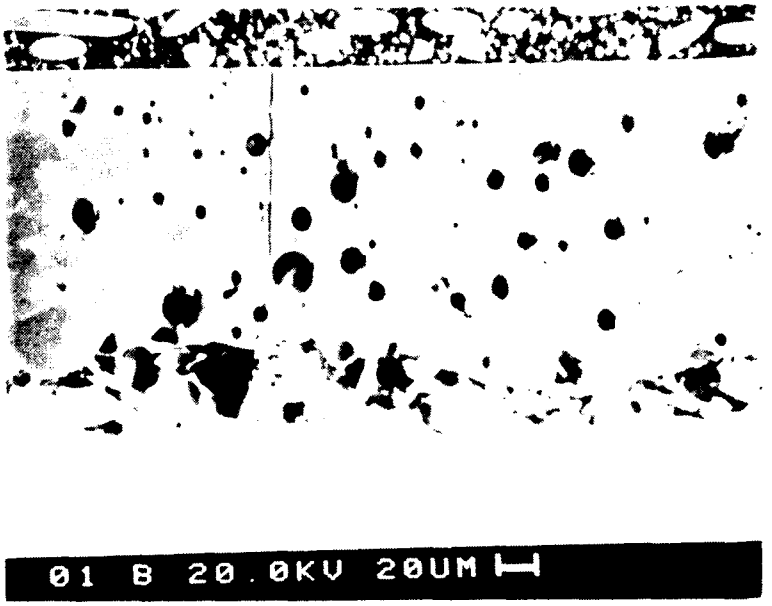


Figure 15. Backscattered electron micrograph of Pl lot 3 sample.

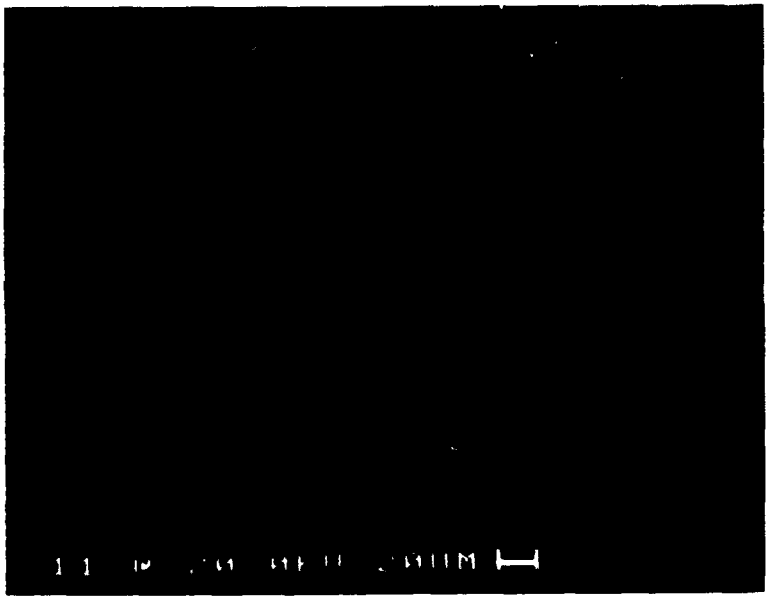


Figure 16. Electron microprobe area scan showing distribution of Na in Pl lot 3 sample.

the magnification is 300X. Figures for PL Lot 2 are not available, because adherence of the enamel to the metal was too poor to allow cutting and polishing of a section. This may be related to the uniquely high thermal expansion of that sample, which is presumably attributable to the metal, causing appreciable mismatch between the enamel and metal. Backscattered electron micrographs are included to provide a better "picture" of each sample cross section; the mottled area of the top of these photos is the potting compound. These figures show the amount and distribution of voids in the enamel of each sample as well as cracking at the metal/enamel interface of some samples, which may reflect stress due to expansion mismatch.

3.4 CONCLUSION PES SUBSTRATES

The substrate evaluation provided information about both the various properties of PES substrates, and about the uniformity of many of these properties from piece to piece and lot to lot.

With the exceptions of thermal conductivity and porcelain softening temperatures, there were no unexpected results in the measured properties of substrates. Thermal conductivities were lower than had been calculated for these materials. Softening temperatures were also lower than expected. In several cases the softening temperature could have been as much as 75 degrees lower than the optimum firing temperatures of certain thick films inks that were used. This situation could lead to distortion of thick film patterns, although in later tests, no such problem occurred.

Dimensionally, the substrates were quite satisfactory. Edge menisci were almost always less than two mils high, and were consistent. Pinholes and bumps in the porcelain were virtually nonexistent. The treatment of the metal before enamelling is critical to the acceptability of the finished substrate as a flat surface is required for processing thick films. Bowed and warped metal will yield bowed and warped substrates. Generally, the substrate suppliers are aware of the need for flatness, and are able to process the metal to obtain flat substrates.

4. THICK-FILM COMPATIBILITY AND GUIDELINES

It has been well established that thick-film materials cannot be processed in the same manner on PES substrates as on alumina substrates. In considering PES substrates for use in mass-produced hybrids it is necessary to define materials properties and limitations and to determine and specify appropriate design and processing guidelines. Therefore a major effort was devoted to the examination of all significant elements of thick film. That effort is described in this section.

4.1 PROBLEMS WITH THICK FILM ON PES

The structure and composition of PES substrates result in a number of properties that potentially limit their function as hybrid substrates. The influence of each of these factors in circuit design and processing was

considered during the experimental portion of the program. These areas include the following:

- o Surface contour, edge meniscus, camber, orange peel, and burrs.
- o "Swimming," or movement of the pattern and other interactions between paste and substrate during firing.
- o Pin-holes and other enamel defects.
- o Alkali ion content.
- o Low temperature firing.
- o High thermal expansion.

In addition, there were processing uncertainties in the following areas:

- o Process detail limitations.
- o Resistor characteristics.
- o Multilayer dielectric capabilities.
- o Testing to MIL-STD-883B.

4.2 EXPERIMENTAL APPROACH

In order to answer these questions, tests were performed using patterns specially designed for conductors, resistors, and dielectrics. Tests were also performed on solders and epoxies as they are used in hybrid circuits.

In each case, testing was designed to define the capabilities of PES-based technology in hybrid applications, and to determine process limitations and optimum processing conditions. Evaluations were based on the use of these materials in the high volumes typical of ordnance applications. The tests were designed to determine as well as possible the following data:

Physical

- o Effect of edge meniscus on printability and utilization of substrate area.
- o Effect of bow and warp on printing and assembly processes.
- o Effect of shear edge and edge roughness on registration and pattern definition.
- o Variation of substrate and thick film performance with normal manufacturing process variation.

Conductors

o Minimum line width and spacing

o Adhesion

o Wire bondability

o Solder wetting, leach resistance, and aged adhesion.

o Effect of firing temperature on metal powder sintering.

Resistors

o Length and width limitations for decades 10 ohms to 1 megohm.

o Termination effects.

o Effects of surface roughness and contour irregularity.

o Establishment of laser trimming criteria.

o Post-trim stability.

Dielectrics

o Pattern resolution.

o Dielectric constant, dissipation factor, and breakdown strength.

o Minimum thickness to eliminate pinholes.

o Compatibility with conductors and substrates.

Vendors for the initial evaluation were selected on the basis of (a) advertised specifications and (b) availability of a full range of resistor materials. It must be emphasized that it was not the intent of this program to evaluate the various inks available on the market at the time the program was in progress. Inks from several vendors were used to enhance the generality of observations on the manner in which thick-film materials performed under the constraints imposed by the PES substrates.

Conductor, dielectric, and resistor inks were purchased in the open market for this testing. The materials and vendors were as follows:

Conductors:

o DuPont: 7711 Pd-Ag, 7712 Pt-Ag, 7713 Ag

o ESL: 9694 Pd-Ag, 9595A Pt-Ag, 9996 Ag

o TFS: 3418 Pd-Ag, 3347 Ag, 3045 Au*

Resistors:

- o DuPont: 7600 Series 15 ohms/sq to 1 Mohm/sq
- o ESL: 3100 Series 10 ohms/sq to 1 Mohm/sq
- o TFS: 600 Series 10 ohms/sq to 100 kohms/sq

Dielectrics:

- o DuPont: 7701
- o ESL: M4030
- o TFS: 1129 TCG
- o EMCA: 9041-1

*Evaluated only for wire bondability.

4.3. CONDUCTORS

4.3.1 Materials and Tests

The conductor inks listed in table 12 were used in this phase of the program. It was felt that these materials gave a sufficiently broad range of properties to cover most applications.

Three silver inks were investigated to cover nonmilitary applications where economy is especially important. Also investigated were three palladium-silver inks, with resistivities (hence, palladium-to-silver ratios) low, medium, and high. Two platinum-silvers, the most expensive of the general purpose inks, were included for comparison; both were apparently low in platinum content. Finally, one gold ink was included as an example of an ink that might be required for high reliability military and medical applications.

Cermalloy 4350 and Plessey-EMD C5800 golds were obtained in the form of fired samples provided by the vendor. They were tested only for wire bondability. The viscosity and solids content of each lot of each ink was measured before initial use as a standard quality control procedure. The following tests were performed on each ink using appropriate test patterns:

- o Fine line resolution
- o Print thickness
- o Thermosonic and thermocompression wire bondability (gold wire)
- o Ultrasonic wire bondability (aluminum wire)
- o Solderability
- o Solder leach resistance
- o Initial and aged adhesion
- o Compatibility with PES substrates
- o Effects of firing temperture on solderability and wire bondability

TABLE 12. PROPERTIES OF CONDUCTORS EVALUATED*

Vendor	Des.	Firing Temp (°C)	Sheet resistivity (m Ω /sq)	Wire Bondability		Solderability	
				Al	Gold	Wetting	LR
Palladium - Silver							
Dupont	7711	650 ±5	50	NA	NA	Exc	5-6(10)
TFS	3418	600 ±20	25 - 30	NA	NA	Exc	30(1)
ESL	9694	625 ±25	4 - 7	No	NS	VG	5-9(10)
Platinum - Silver							
Dupont	7712	650 ±5	4	NS	NS	Exc	4(10)
ESL	9595A	625 ±25	5 - 8	Yes	NS	G	2-4(10)
Silver							
Dupont	7713	540	3	NS	NS	Exc	NS
ESL	9996A	625	2 - 4	Yes	NS	G	2(10)
TFS	3347	510 - 600	2 - 2.5	Yes	Yes	VG	5(1)
Gold							
TFS	3045	575 - 900	4	Yes	Yes	NA	NA

* NA = not applicable
  Exc = excellent
  VG = very good
  G = good
  NS = not specified
  LR = Leach resistance. The number of dips in 62 solder to cause de-wetting. The figures in parenthesis are the durations of each dip in seconds.

4.3.2 Printing-Resolution

No formalized program to characterize printing characteristics and quality of conductor inks on PES substrates was carried out. However, two test patterns were used to provide a qualitative measure of capabilities, and identify limitations, of conductors printed and fired on PES.

First, the fine-line test pattern shown in figure 17 was printed on a few 1 x 2 in. substrates. The pattern comprises three basic elements. First are 12 meander lines with widths and spacings ranging from 0.002 to 0.007 in., with pads for measuring continuity. Second are pairs of pads separated by gaps ranging from 0.003 to 0.025 in. These patterns are arranged so that each line is printed parallel and perpendicular to the direction of squeegee travel. Third is a group of concentric similar triangles with lines ranging from .0035 to .010 inches, oriented to fall 0°, 45°, 60°, and 90° to the direction of squeegee travel. All printing was done with a 325-mesh, 0.0011-in. emulsion, stainless steel screen with mesh angle 45°.

A second pattern shown in figure 18 used principally for wire bond testing also contained a test for print resolution. Pairs of parallel lines each contained line widths of 3, 5, 7 and 9 mils. The separation of the lines also varied from 3 to 9 mils.

Figure 17 is a photograph of a fired sample of the former test pattern. Even the finest lines and spaces were resolved. In addition, diagonal lines were printed over the meniscus without distortion.

A printed and fired sample of the wire bond test is shown in figure 18. On the part shown, the 3-mil line segments and 3 mil spaces were printed successfully in both the longitudinal and transverse directions.

On the basis of experience with these patterns it was concluded that satisfactory print resolution can be achieved for lines and spaces as small as 5 mils, provided that good-quality screens are used and the ink viscosity is within specification.

4.3.3 Solderability

Solder wetting, leach resistance, and adhesion before and after aging were evaluated on test patterns as shown in figure 19 using the silver-bearing conductor inks listed in table 12. Substrates from both ECA and GE were used. Three firing temperatures were used for each group: the manufacturer's recommended temperature, and 25°C above and 25°C below the recommended temperature. This variation in firing temperature was used, since there are circumstances when the inks cannot be fired at precisely the recommended temperature.

The wetting and leach resistance studies are described in section 4.3.3.1, and adhesion studies in section 4.3.3.2.

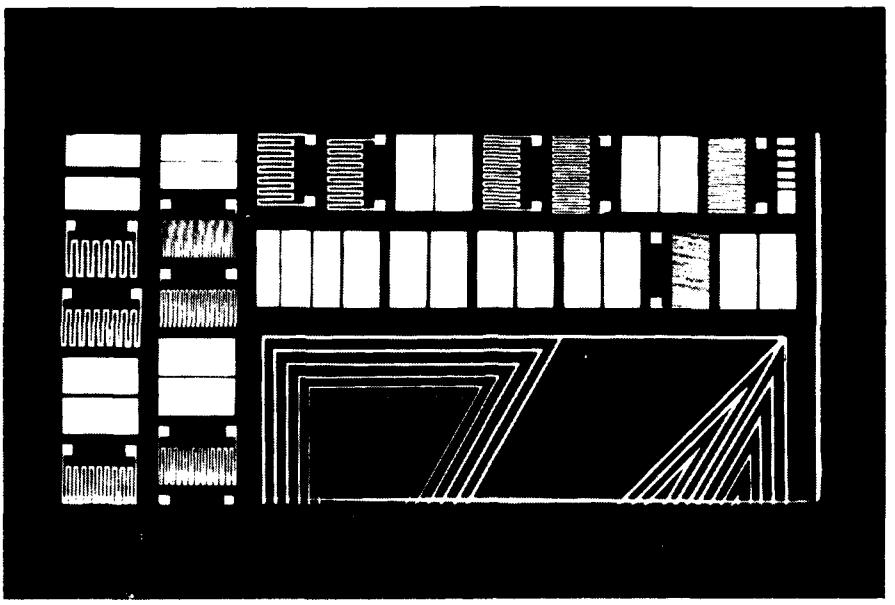


Figure 17. Fine-line conductor test pattern.

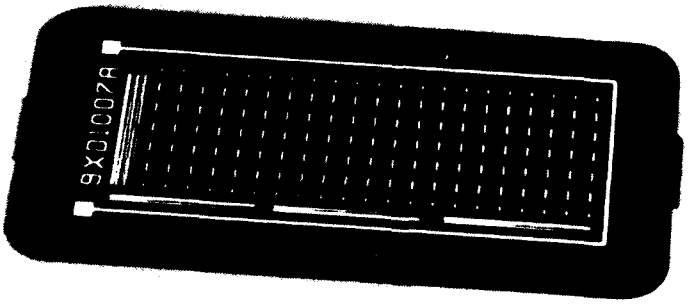


Figure 18. Wire bondability and conductor resolution test pattern.

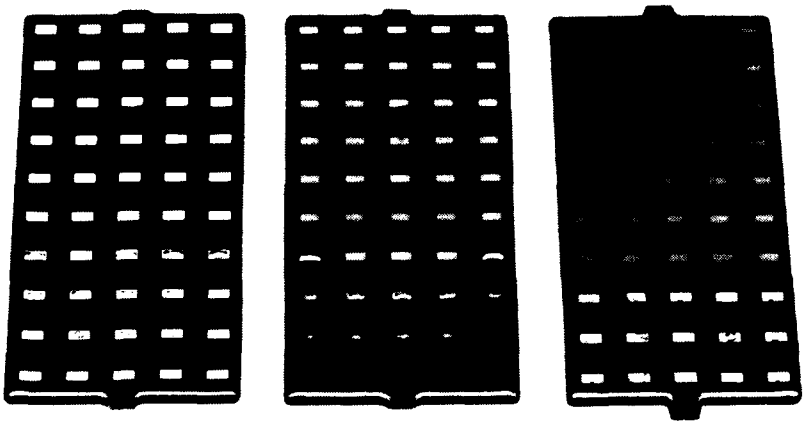


Figure 19. Solderability test pattern

4.3.3.1 Wetting and Leach Resistance

4.3.3.1.1 Experimental Procedure

Preliminary leach resistance studies were performed on silver-bearing conductor inks fired at 600°C. Later, these properties on substrates fired at different temperatures as described above were evaluated. Tests were performed with two solder compositions: 96-percent tin/4-percent silver (96Sn4Ag) at 250°C, and 62 percent tin/36-percent lead/2-percent silver (Sn 62) at 220°C.

Test patterns consisting of a 5 row by 10-column array of 0.050 by 0.100 in. pads were printed with each of the conductor inks, on 1 x 2 in. substrates. Patterns were fired in a belt-type thick film firing furnace, for all firing temperatures.

Fired thicknesses of the films were measured on samples representative of each ink. One half of each substrate was burnished, after which the substrates were cleaned by immersion and brushing in inhibited methyl chloroform and 2-isopropanol, respectively.

Individual substrates being tested were first heated on a hot plate to approximately 125°C to reduce the amount of thermal shock felt upon immersion in molten solder. The substrate was then rapidly dipped in RMA flux followed by immersion to a depth of approximately 0.5 in. of the unburnished end in

molten solder. After an initial 10-s dip in the solder bath, the solder acceptance-wettability of the conductor pads was determined by low-power microscopic examination. The percentage of coverage of the immersed pads was estimated and recorded.

The complete dipping procedure and subsequent examination were repeated until 75 percent of the immersed pads would no longer accept solder. The number of dips required to cause 25-, 50-, and 75-percent dewetting were recorded.

Experience has shown that the estimate of pad area coverage, although subjective, is reliable within 10 percent when done by an experienced technician.

4.3.3.1.2 Results-Substrates Fired at 600°C

The results obtained in the initial testing in Sn62 and 96/4 SnAg solder are presented in tables 13 and 14, respectively. As expected, leaching was much less severe in the Sn62 than in the 96/4 SnAg. Unexpectedly, the pure silver films were not leached as rapidly in Sn62 as were the films containing platinum and palladium.

It was observed that the silver-bearing films were never leached completely away, as frequently happens on alumina substrates. Rather, the pad would become unsolderable even though it would appear to have a substantial thickness remaining. One hypothesis to explain this phenomenon is that the low firing temperature of the films precluded alloying of the silver with the platinum ore palladium. Concequently, the silver component in the platinum and palladium-silver films is selectively dissolved away by the solder until only the platinum or palladium remains, and these materials are not readily wetted by the solder.

4.3.3.1.3 Effect of Substrate Firing Temperature

Since the PES conductors demonstrated reasonably good solder wetting and leach resistance by thick film standards, a more extensive evaluation was carried out. Specifically, the effects of peak firing temperature, substrate type, wetting, leach resistance, and adhesion were investigated.

Both ECA and GE substrates were printed with the solder pad pattern with the eight inks listed in table 12. All substrates in a particular paste group were divided into three subgroups. Each of these subgroups was fired at a different peak temperature: the manufacturer's recommended temperature and 25 degrees above and below the recommended temperature. These substrates comprised the test sample for both leach resistance and adhesion tests that followed.

TABLE 13. INITIAL TEST RESULTS, SOLDER WETTING AND LEACH RESISTANCE, Sn62 Pb36 Ag2 SOLDER, 220 ± 3°C

Material	Type	Fired print thickness (10^{-3} in)	Initial wetting (%)	Number of dips to reduce wetting to 75%	50%	25%
DP 7711	PdAg	0.64	90	3	4	5
DP 7712	PtAg	0.60	95	18	27	30
DP 7713	Ag	0.27	85	1	2	12
ESL 9694	PdAg	0.80	100	22	26	30
ESL 9595A	PtAg	0.51	100	9	14	20
ESL 9996A	Ag	0.50	100	22	25	33
TFS 3418	PdAg	0.62	100	10	12	14
TFS 3347	Ag	0.34	90	3	11	14

Table 14. INITIAL TEST RESULTS, SOLDER WETTING AND LEACH RESISTANCE, 96Sn 4Ag SOLDER, 250 ± 3°C

Material	Type	Fired print thickness (10^{-3} in)	Initial Wetting, (%)	Number of dips to reduce wetting to 75% Percent	50% Percent	25% Percent
DP 7711	PdAg	0.64	100	5	7	9
DP 7712	PtAg	0.60	95	7	8	9
DP 7713	Ag	0.27	100			1
ESL 9694	PdAg	0.80	100	6	7	9
ESL 9595A	PtAg	0.51	50		1	2
ESL 9996A	Ag	0.50	90			5
TFS 3418	PdAg	0.62	100			4
TFS 3347	Ag	0.34	50			3

The wetting and leach resistance tests were done as described earlier. The results obtained within each subgroup varied greatly, part of which can be attributed to the subjectivity of the test.

The results of all the tests done are summarized in table 15. The numbers in each column represent the number of 10-second dips required to cause 25-percent dewetting.

Since the objective of the test was to identify problems and characteristics which are peculiar to solderable films on PES substrates, the discussion will be confined to points which are believed to address that objective.

DP7711: Wetting was fair to good for all firing temperatures. Leach resistance improved to optimum at 650°C, but deteriorated at 675°C.

ESL 9694: Wetting and leach resistance were good to excellent on substrates fired at 600°C, 625°C, and 650°C.

TPS 3418: Wetting was fair on 575°C substrates, improving to good on 600°C and excellent for 625°C units. Leach resistance of these substrates showed the same pattern, the best results being obtained with substrates fired at 625°C, the highest temperature used.

DP7712: Wetting was good on substrates fired at 600 and 625°C, but deteriorated at 650°C and was very poor on substrates fired at 675°C. Leach resistance varied even on substrates fired at the same temperature, but was often very good.

Table 15. Effect of Firing Temperature On Solder Wetting and Leach Resistance (LR)

Material	Wetting and leach resistance* at various firing temperatures									
	575		600		625		650		675	
DP 7711	-		-		F	2-3	F	5-13	F	2-4
DP 7712	-		G	5-15	G	4-5	F	7-13	N**	
DP 7713	-		-	1	P	1-2	P	6-8	N**	
ESL 9694	-		G-E	7-15	G-E	15+	G-E	15+	-	
ESL 9595A	-		G	5	G	4-15	P	9-10	-	
ESL 9996A	-		F-G	4-15	G	4-5	G	5-11	-	
TFS 3418	F	7-8	G	9	G-E	10-12			-	
TFS 3347	G	3	P-F	1-3	P	3			-	

The letters preceding many of the numbers are an assessment of the wetting; i.e., P for Poor wetting, F for Fair, G for Good, E for Excellent, and N for not solderable.

* Leach Resistance. Number of 10-second dips required to cause 25 percent dewetting

** Did not wet initially. Achieved 50 percent wetting after burnishing, but dewetted very rapidly.

ESL 9595A: Wetting was good on substrates fired at 600°C and 625°C, only fair to poor on 650°C units. Substrates fired at 675°C were almost unsolderable. Leach resistance was variable, and appeared to be best at 625°C.

DP7713: On all substrates fired from 600°C to 675°C wetting was poor. Leach resistance is difficult to evaluate because of the poor initial wetting.

ESL 9996A: Performance with regard to both wetting and leach resistance was inconsistent for all substrates, ranging from poor to excellent.

TPS 3347: Wetting was good on samples fired at 575°C, but was poor on substrates fired at higher temperatures. Leach resistance was poor on all substrates.

Although the results of these tests are quite variable, as are similar tests performed on alumina substrates, it is probably valid to say that

solderable thick films can be used on PES substrates in the same manner as they are used on alumina substrates, without changing circuit layouts.

4.3.3.2 Solder Adhesion

4.3.3.2.1 Procedure

Substrates from each of the 48 groups described in the previous section were subjected to 90° peel, or "Dupont" adhesion testing. Straight segments of #22 A.W.G. tin-plated copper wire with crooks at one end were laid across a row of pads and held in place for soldering by being hooked around the edge of the substrate. Usually, four wires were attached to each substrate. With the wires attached, the substrates were coated with RMA flux and dipped in Sn62 solder at 220°C. Each wire was bent vertically approximately 0.05 in. above each pad.

For testing, the substrate was clamped in a fixture in an Instron Model TTCM-1 tensile strength tester. A strain rate of one inch per minute was used in all cases. Although each wire was soldered to five pads in tandem, only the first pad was pulled prior to aging. After the initial pull tests, each substrate was aged for 168 hours at 125°C before repeating the test.

The failure modes fell into five categories, which are defined below.

A. Wire is pulled out of the solder, leaving an almost intact impression in the solder.

B. Porcelain is lifted from the substrate at the tip of the pad where the force initiates. The rest of the break is caused by wire pulling out of the solder, as in Type A.

C. The solder mound lifts from the metalized pad. Usually the entire pad is lifted intact. Occasionally only the solder between the wire and the substrate is lifted.

D. Porcelain is lifted at the tip of the pad. The rest of the break is a solder lift, as in Type C. Occasionally, other small areas of porcelain are pulled out of the substrate.

E. The entire pad--solder, metallization, and a finite thickness of porcelain--is lifted intact. Occasionally only the area directly under the wire is affected.

4.3.3.2.2 Solderability Results

Figures 20 through 27 show the results of these measurements for each ink used. Each figure shows the mean, maximum, and minimum of tensile force required to break the solder joints, for each temperature used for the ink depicted. Values are presented for ECA and GE substrates, as are the results before and after thermal aging.

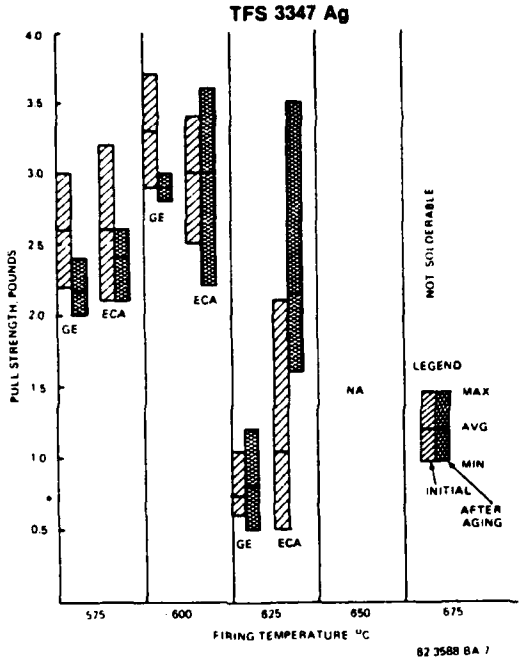


Figure 20. Results of Solder Pull Tests - TFS3347 Ag

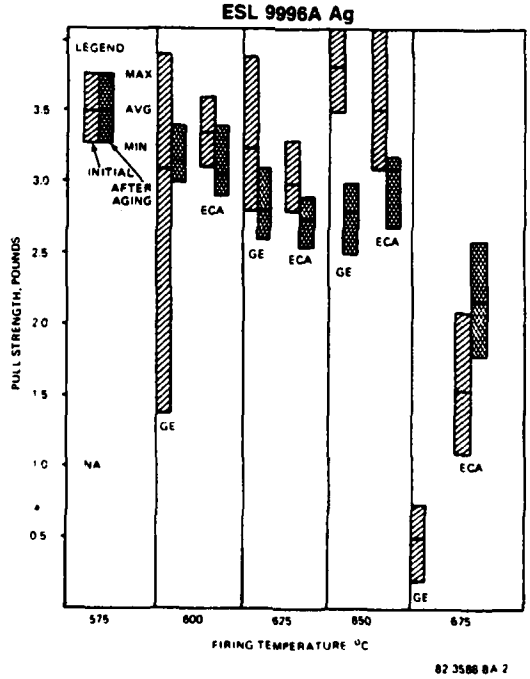


Figure 21. Results of Solder Pull Tests - ESL996A Ag

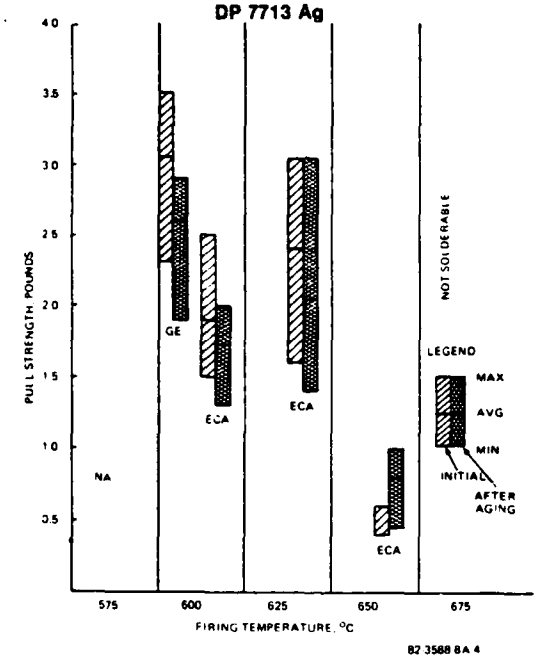


Figure 22. Results of Solder Pull Tests - DP7713 Ag

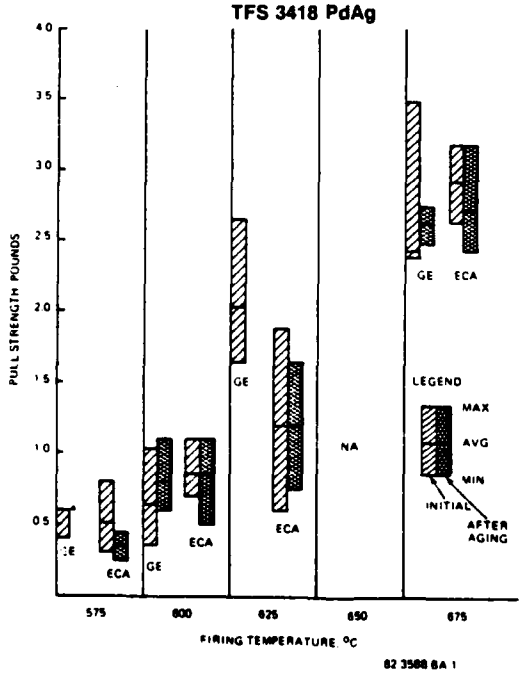


Figure 23. Results of Solder Pull Tests - TFS3418 PdAg

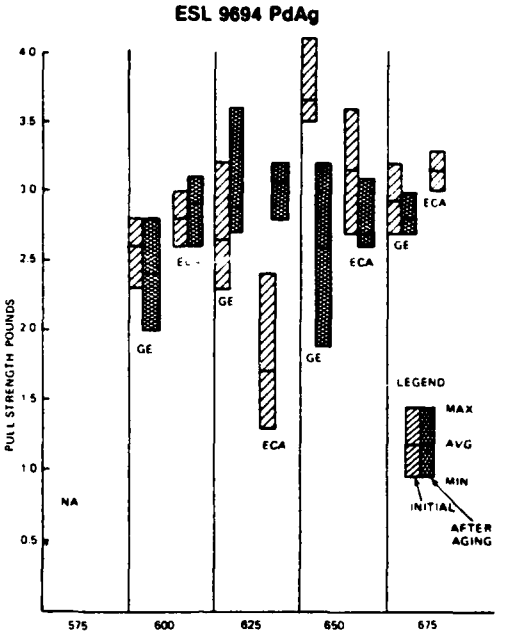


Figure 24. Results of Solder Pull Tests - ESL9694 PdAg

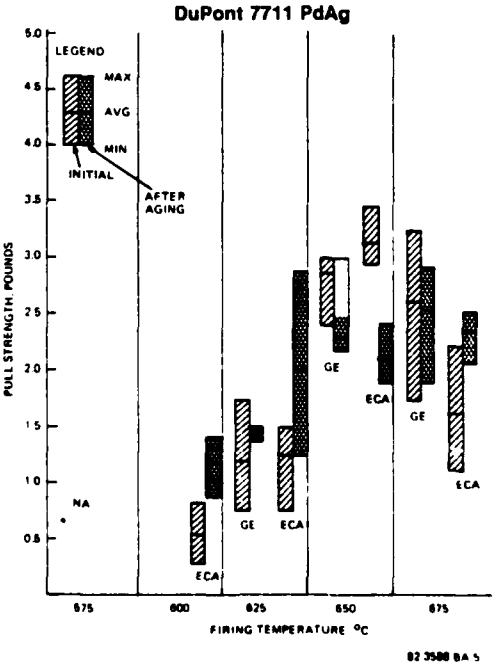


Figure 25. Results of Solder Pull Tests - Dupont 7711 PdAg

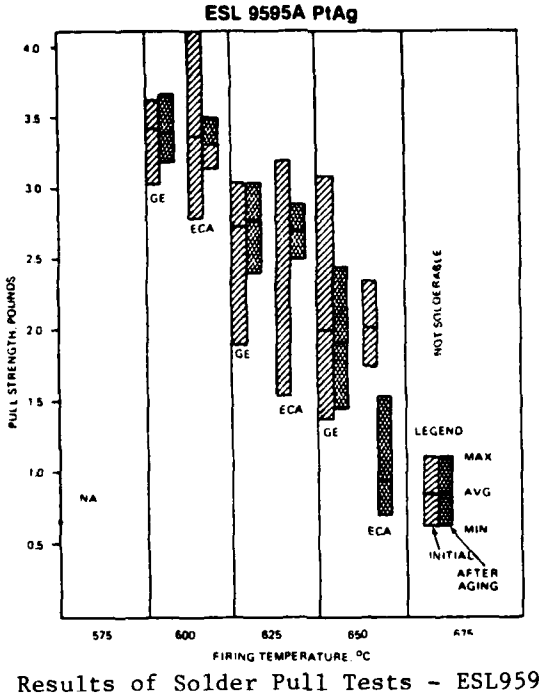


Figure 26. Results of Solder Pull Tests - ESL9595A PtAg

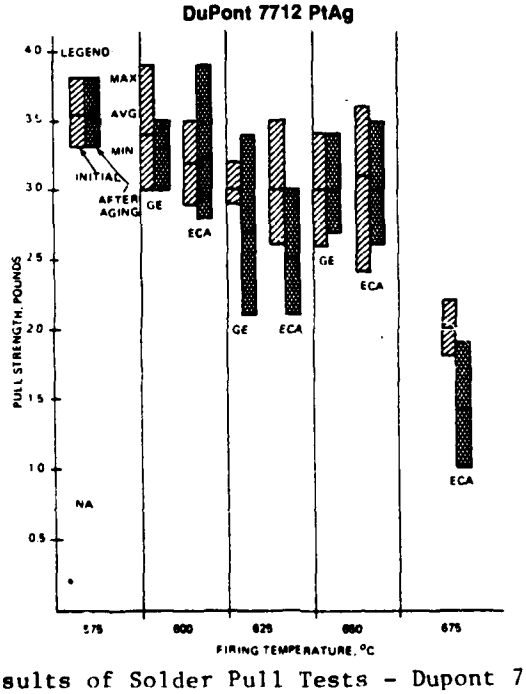


Figure 27. Results of Solder Pull Tests - Dupont 7712 PtAg

As was the case with the solder leach resistance, the most notable feature of the data is the deviation or spread. Several factors are believed to contribute to this spread. First, the five distinct failure modes observed were treated equally in reducing the data. Second, several of the materials were only marginally solderable. As a result, the areas of the solder joints could vary considerably. Third, the test is influenced by many variables, such as soldering time and elapsed time between soldering and pulling, which were not well controlled. In spite of the data spread, a number of general observations can be made from an analysis of the failed solder joints. Each joint was examined and placed into one of the categories listed in table 15. The predominant failure mode for that substrate group was also established. At the same time the solder coverage on the remaining pads was observed and characterized as before.

The failed solder joints for each group of substrates are characterized and listed below by paste type, firing temperature, and substrate type. Several characteristics seem to be shared by the various subgroups, which are discussed in the following paragraphs. Two initial points should be made, however. First, there were no outstanding differences between the performances of the GE and ECA substrates. Second, there was not a single observed instance where the thick film metalization peeled from the porcelain surface and left the porcelain intact. Whenever a pad lifted, porcelain was always attached to the pad. The porcelain remaining where the pad had been would have a jagged surface characteristic of fractured glass. To support this observation we have attempted to peel numerous metal pads from subtrates using a razor blade. In every case thick film material was scraped away, but it was not possible to lift a pad.

Platinum-silver. The failed joints for both platinum silvers tested, ESL 9595A and Dupont 7712, almost always exhibited a degree of porcelain removal. This was especially true with substrates which showed good solder coverage of the pads. The average failure strengths declined as firing temperature increased for both types of ink.

Palladium-silver. The solder joints for palladium-silver pads exhibited an overwhelming majority of C-type failures. In contrast to the experience with platinum-silver, the average failure strengths increased as firing temperature increased.

The surfaces of the pads after destructive pulling appeared typically to have had part of the film removed. It was as if the film were in layers loosely bonded to each other, and the failures occurred at the layer interfaces. As firing temperatures increased, the interlayer bond strength would increase, leading to higher breaking strengths.

Silver. The ESL 9996A and TFS 3347 silvers were similar to the platinum-silvers in failure mode. The Dupont 7713 silver showed such poor solderability that it would be misleading to include it in this analysis. The failures of joints on the 3347 and 9996A usually involved porcelain removal, as long as good solder coverage could be achieved. The strength of the 9996A samples tended to decrease as firing temperature increased. The 3347 had good solderability only when fired at 575°C and 600°C, and this kind of trend could not be discerned for this sample.

4.3.3.3 Conclusion: Solderability Testing

The solder wetting, leach resistance, and adhesion strength tests were intended to disclose common, generally applicable characteristics of solderable thick films on PES substrates. The tests performed required a considerable amount of subjective interpretation, and for this reason the results must be treated carefully. Similarly, the scatter in the data, particularly in the adhesion tests, makes the statistical significance of the tests marginal. However, by analyzing the trends which could be discerned and correlating them with other information and knowledge, it is possible to make hypotheses which may be useful.

1. Adhesion of film to porcelain. Suggests strong interaction even at low temperatures.

2. Anomalous apparent leach resistance of pure silver compared to other materials. (Also noted by Linder of G.E.)

   Leach resistance is equated with percent dewetting. The PdAg and PtAg dewet rather than leach, due to selective dissolution of the silver. The remaining films are platinum rich or palladium rich, and are not easily wet with solder.

   This condition suggests that the low firing temperature required by these substrates is insufficient to promote alloying of the metallic constituents.

3. Failure mode of solder joints on PdAg pads. Failures of these joints seemed to occur within the films. This phenomenon suggests primarily that very little sintering of the metal powders has taken place. Also, the firing temperatures of thick films for PES substrates are in the range where palladium oxide forms, but below the range where it decomposes. The palladium oxide may inhibit sintering of the powders. It was observed that solder joints on Pd Ag films fired at 650°C failed by removal of porcelain, indicating that the cohesion of the film was increased. However, the 650°C firing temperature usually resulted in degraded solderability.

4.3.4 Wire Bondability

An essential technology for fabrication of bare chip (integrated circuit die) hybrid circuitry is attachment of fine (0.001 in.) wire to chips and substrates. Three basic techniques exist in the hybrid industry for doing this: thermocompression, in which a gold wire is bonded to a metallized semiconductor chip and substrate by simultaneous application of heat and pressure; ultrasonic, in which ultrasonic energy and pressure are applied to the wire and surface to achieve a bond; and thermosonic, in which heat, pressure, and ultrasonic energy are used. The completed bonding operation forms a metallurgical bond between the chip and the substrate.

For the present investigation, emphasis was placed on thermosonic bonding of 1-mil gold wire, since this is the newest technology and the one used in

all commercially available automatic wire bonders. Limited experimentation was also done with thermocompression gold and ultrasonic aluminum bonding.

In a wire bonding operation there are many variables which must be controlled for a successful outcome. Surface cleanliness, wire characteristics, capillary (bonding tips) shape and size, bonding pressure, substrate temperature, ultrasonic energy level and duration, and substrate clamping--all determine the quality and reliability of the bonds achieved. Even when surfaces known to be wire bondable (e.g., plated gold on alumina) are used the conditions cited above must be properly handled. In attempting to evaluate the wire bondability of a new material on a new substrate it is necessary to find, if possible, the set of conditions which will result in satisfactory wire bonds for that material.

In this program we are dealing with a substrate surface relatively unknown for hybrid assembly. In addition, the metal films formulated for porcelain fire at a much lower temperature than the films with which most hybrid experience has been gained. Thus, bonding on PES materials was performed with little previous experience to use as guidance. Seven bonding variables had to be optimized for each material, in order to achieve bonds of sufficient adhesion to survive until test. Obviously, this investigation could require far more effort than was possible in the present program. For this reason, results must be treated as preliminary.

Materials which presented difficulty in wirebonding in this program might have been quite wire-bondable if different bond schedules or wire types were used to achieve bonds.

4.3.4.1 Description of Test

PES substrates from ECA and GE were printed with test patterns with each of the eight silver-bearing conductors described previously, and one gold formulated for PES. All substrates were fired at 600°C.

In the first tests, 25 wires were ball and stitch bonded to each substrate. Loop height was uniformly 40 mils, and the separation of ball and stitch was 50 mils. All wires were pulled to destruction using a Mech-El Model BT-201 or Unitek Model 6-095-06 Pull Tester. The grams-force required to destroy the bond, and the mode of failure, were recorded. In evaluating a material, the following guidelines were used:

- Numbers of multiple hits required to achieve a bond. If more than one "hit" or attempt is required to bond the wire to the substrate, it is futile to consider automatic wirebonding.

- Numbers of failures in destructive pull testing with less than 3 grams force. Bonds would fail a nondestructive pull test enough to indicate an unsatisfactory process.

- Numbers of ball and stitch lifts in destructive pull testing. In an established process where well characterized materials are used, there should be no ball or stitch lifts, which are indicative of an unreliable

bond. In evaluating new materials, bond lift counts serve as an index of bonder process development.

- o Relative percentages of wire breaks and stitch breaks. A high percentage of stitch breaks is undesirable and indicative of a process which needs improvement.

For each conductor in the evaluation, an attempt was made to establish optimum wire bonder operating conditions. Ultrasonic time and power, capillary force, and substrate temperature were varied. Surface treatments as described in table 16 were used. After a combination of settings were found which resulted in successful bonds, several (~10) bonds were made and destructively pulled. The process was repeated until the best results were achieved. Twenty-five bonds were then made using those conditions. The wires were destructively pulled, and breaking forces and failure mode recorded.

TABLE 16. TREATMENT OF WIRE BOND TEST SAMPLES

Code	Description of Treatment
A	Unburnished
B	Burnished, fiberglass brush
C	Plasma cleaned
D	Overprinted, cermalloy 4300 UF
E	Aluminum wire

4.3.4.2. Silver-Bearing Conductors

The results of all wire bondability tests using gold wire thermosonic bonding or aluminum wire ultrasonic bonding on all silverbearing conductors are summarized in tables 17 through 23. Attempts to bond wires to Dupont 7711 Pd-Ag were unsuccessful; hence there is no table for that material.

Histograms depicting the ranges of bond strengths for the best sample of each conductor type are presented in figures 28 through 34.

Although there were differences in the way each paste performed, certain characteristics were shared by all. First, bonding to the palladium-silvers always proved difficult. Burnishing these materials always rendered them unbondable within the ranges of parameters tried. With all materials, the failure mode was most often a stitch break. A few stitch lifts were seen but no ball lifts. Forces required to destroy the loop varied considerably, very probably because the predominant failure mode was stitch breakage. (The ultimate tensile strength of the wire is uniform. However, the damage to the wire in making the stitch bond, which eventually causes the failure, is variable and unpredictable.) Finally, with all materials, there were significant numbers of failures below 3 grams. This large number of failures precludes the passing of any nondestructive pull testing.

TABLE 17. WIRE BOND PULL TEST RESULTS, DUPONT 7712 PtAg

Bond type[a]	Quantity	Treatment[b]	Destructive force[c] (gm)		Failure mode distribution (%)			
			Mean	SD	Wire	Stitch	Lifts	Under 3 gm
TS	10	A	4.7	2.5	10	90	0	30
TS	25	A	6.5	1.5	48	52	0	8
TS	25	A	6.5	2.2	16	84	0	12
TS	23	B	1.3	1.2	0	100	0	76
TS	10	D,A	8.9	0.8	90	10	0	0
US	24	E,A	5.2	4.1	0	75	25	40

a TS = Thermosonic
US = Ultrasonic
b See codes in table 16
c SD = Standard Deviation

TABLE 18. ESL 9595A PtAg WIRE BOND PULL TEST RESULTS

Bond type[a]	Quantity	Treatment[b]	Destructive force[c] (gm)		Failure mode distribution (%)			
			Mean	SD	Wire	Stitch	Lifts	Under 3 gm
TS	26	A	6.2	2.2	23	77	0	12
TS	0	B	Could not attach bonds					
TS	25	A	6.9	2.3	24	76	0	12
TS	25	B	3.9	1.5	8	92	0	12
TS	25	A	5.2	2.0	0	100	0	16
US	12	E	8.5	2.8	0	100	0	0

a TS = Thermosonic
US = Ultrasonic
b See codes in table 17
c SD = Standard Deviation

TABLE 19. WIRE BOND PULL TEST RESULTS, DUPONT 7713 Ag.

Bond type[a]	Quantity	Treatment[b]	Destructive force[c] (gm)		Failure mode distribution (%)			
			Mean	SD	Wire	Stitch	Lifts	Under 3 gm
TS	10	C	8.1	1.3	80	10	10	0
TS	25	A	5.4	2.5	20	80	0	28
TS	26	C	6.5	2.2	44	56	0	8
TS	25	A	3.6	2.1	0	100	0	36
TS	23	B	2.1	1.6	4	96	0	83
TS	10	A,D	9.3	0.6	100	0	0	0
US	18	A,E	5.9	4.2	0	84	16	28

a TS = Thermosonic
US = Ultrasonic
b See codes in table 17
c SD = Standard Deviation

TABLE 20. ESL 9996 Ag. WIRE BOND PULL TEST RESULTS

Bond type[a]	Quantity	Treatment[b]	Destructive force[c] (gm)		Failure mode distribution (%)			
			Mean	SD	Wire	Stitch	Lifts	Under 3 gm
TS	10	C	6.4	2.6	40	60	0	10
TS	25	A	7.7	1.2	60	40	0	0
TS	23	C	7.1	1.6	39	61	0	0
TS	25	A	7.7	2.6	28	68	4	4
TS	25	B	4.1	3.1	0	100	0	48
US	16	E	6.0	3.9	0	81	19	25
TS	30	B	7.6	1.5	40	47	13	0
TS	25	A	5.3	2.2	4	96	0	4
TS	25	B	4.7	1.6	0	64	36	24

a TS = Thermosonic
US = Ultrasonic
b See codes in table 17
c SD = Standard Deviation

TABLE 21. WIRE BOND PULL TEST RESULTS, TFS 3347 Ag

Bond type[a]	Quantity	Treatment[b]	Destructive force[c] (gm)		Failure mode distribution (%)			
			Mean	SD	Wire	Stitch	Lifts	Under 3 gm
TS	10	C	7.3	2.0	30	70	0	10
TS	25	A	5.9	2.3	28	72	0	8
TS	25	C	7.6	1.5	56	44	0	0
TS	25	B	2.2	2.2	40	96	0	72
TS	25	A	5.2	2.1	8	92	0	16
US	37	E	9.7	4.4	0	97	3	8

a TS = Thermosonic
US = Ultrasonic
b See codes in table 16
c SD = Standard Deviation

TABLE 22. ESL 9694 PdAg. WIRE BOND PULL TEST RESULTS

Bond type[a]	Quantity	Treatment[b]	Destructive force[c] (gm)		Failure mode distribution (%)			
			Mean	SD	Wire	Stitch	Lifts	Under 3 gm
TS	26	A	6.6	1.7	31	69	0	0
US		E	Not Bondable					
TS		A & B	Not Bondable					
TS	10	D	9.5	0.6	100	0	0	0

a TS = Thermosonic
US = Ultrasonic
b See codes in table 16
c SD = Standard Deviation

TABLE 23. WIRE BOND PULL TEST RESULTS. TFS 3418 PdAg

Bond type[a]	Quantity	Treatment[b]	Destructive force[c] (gm)		Failure mode distribution (%)			
			Mean	SD	Wire	Stitch	Lifts	Under 3 gm
TS	25	A	5.1	2.4	28	60	12	16
US	0	E	Not Bondable					
TS	10	D	9.3	0.9	100	0	0	0

a TS = Thermosonic
US = Ultrasonic
b See codes in table 16
c SD = Standard Deviation

Results of ultrasonic aluminum wire bond tests are included in the tables. Attempts to bond to the palladium silvers were unsuccessful. Better results were obtained with the pure silvers and platinum silvers, but all results were marginal.

Effort was also devoted to making thermocompression bonds using 1-mil gold wire. With a capillary temperature at 465°C and substrate temperature of 160°C, attempts on all materials were poor or completely unsuccessful. Raising the substrate temperature to 235°C made it possible to achieve bonds on the pure silvers, but the other materials were not bondable. This effort was not pursued.

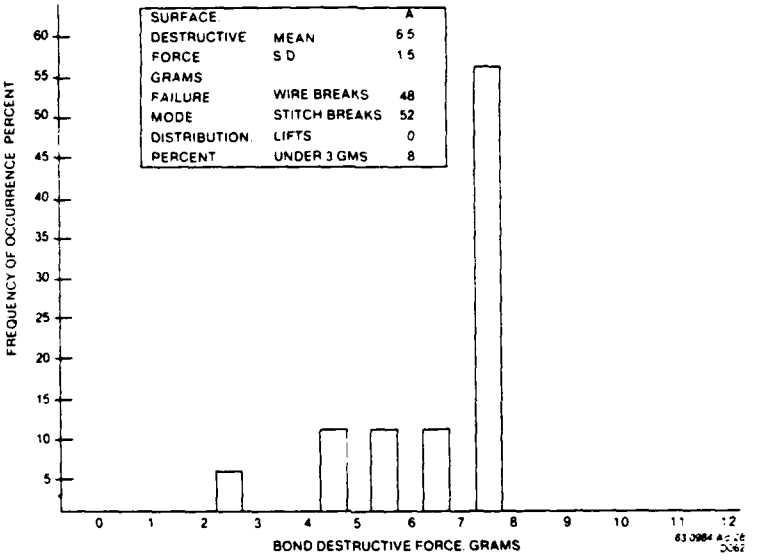


Figure 28. Distribution of pull test failures, thermosonic bonds, Dupont 7712 AgPt

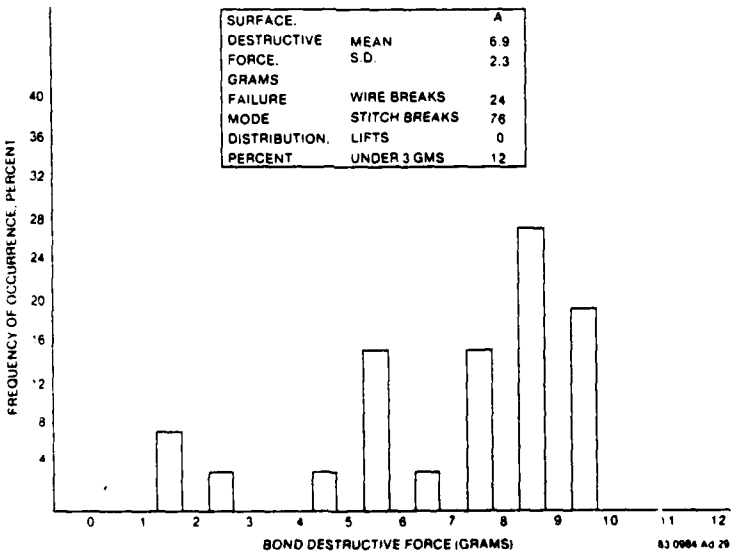


Figure 29. Distribution of pull test failures, thermosonic bonds, ESL 9595A PtAg

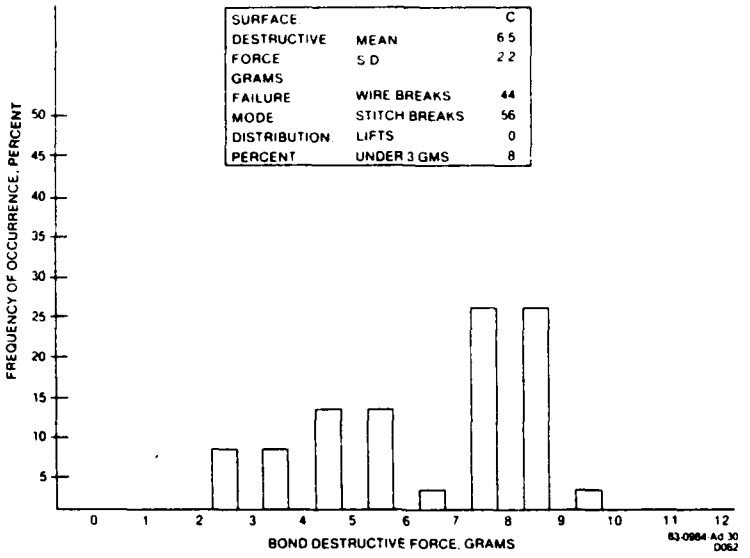


Figure 30. Distribution of pull test failures, thermosonic bonds, Dupont 7713 A

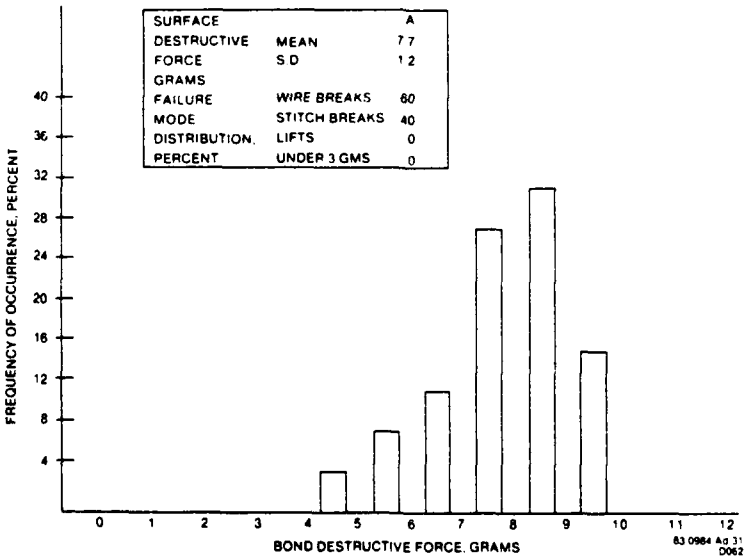


Figure 31. Distribution of pull test failures, thermosonic bonds, ESL 9996A Ag

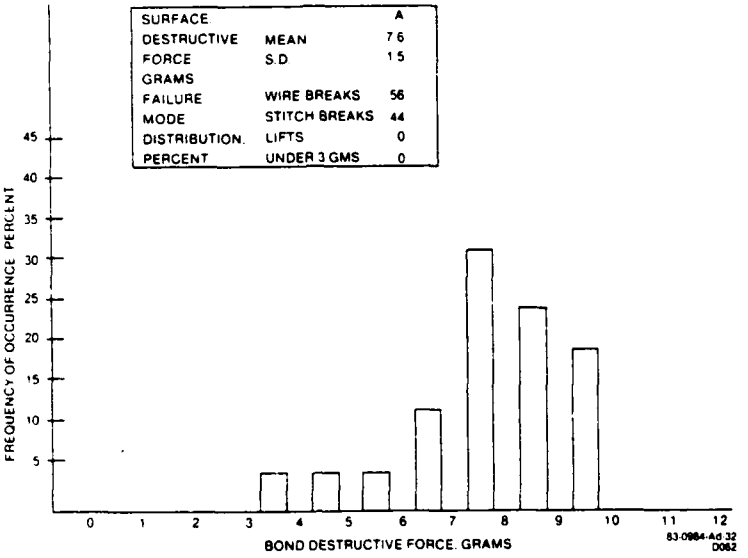


Figure 32. Distribution of pull test failures, thermosonic bonds, TFS 3347 Ag

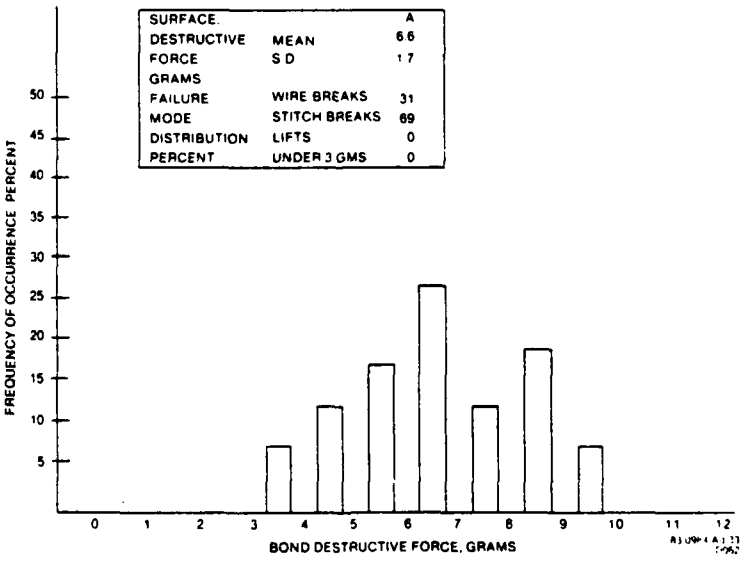


Figure 33. Distribution of pull test failures, thermosonic bonds, ESL 9694 PdAg

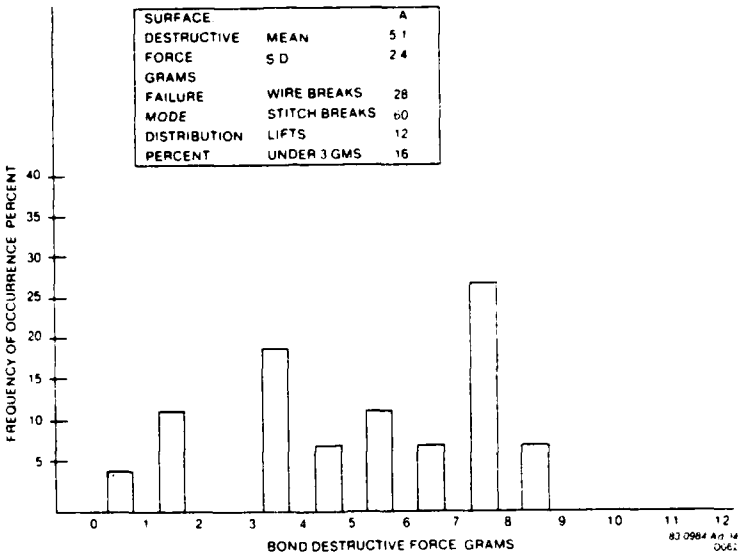


Figure 34. Distribution of pull test failures, thermosonic bonds, TFS 3418 PdAg

4.3.4.3 Gold Conductors

The major portion of the effort to establish satisfactory wire bonding to PES substrates was devoted to work with gold conductor inks. Most of this work was done with Thick Film Systems 3045. In addition, a few substrates with Cermalloy 4350 and Plessey C5800 golds (provided as fired by the vendor) were evaluated.

4.3.4.3.1 TFS 3045

Initial tests indicated that the TFS 3045 could be wire bonded with more success than had been achieved with the silvers. Table 24 and figure 35 and 36 present the results of several tests made after numerous attempts to optimize the bonding. It can be seen that, relative to the silvers, mean breaking strengths are higher, the data spread is less, there are fewer lifts and low value breaks, and a higher percentage of breaks are in the wire, rather than the stitch. However, the results are still inferior to those achieved on conventional gold films on alumina. This problem is discussed later.

Table 24 also presents results for thermocompression bond testing on TFS 3045. Substrate and capillary temperatures were 235°C and 465°C, respectively. In contrast to our experience with the silver-bearing thick film inks, thermocompression bonding resulted in greatly improved wire bonds. For both burnished and nburnished films, the distributions were narrow, as can be seen in figure 37. Most significantly, all breaks were in the wire.

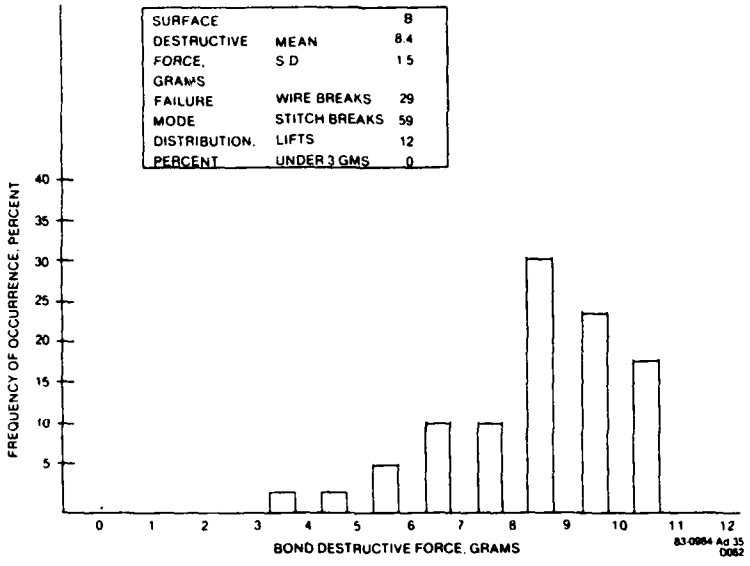


Figure 35. Distribution of pull test failures, thermosonic bonds, TFS 3045 Au, Burnished.

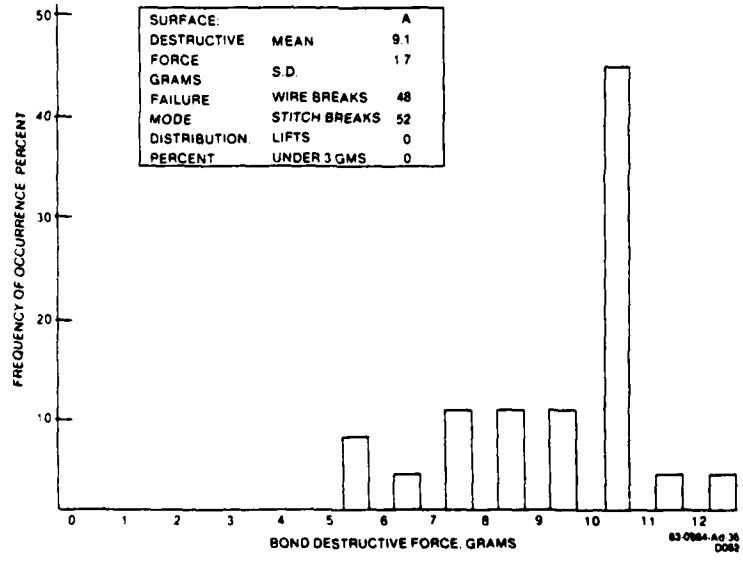


Figure 36. Distribution of pull test failures, thermosonic bonds, TFS 3045 Au, Unburnished.

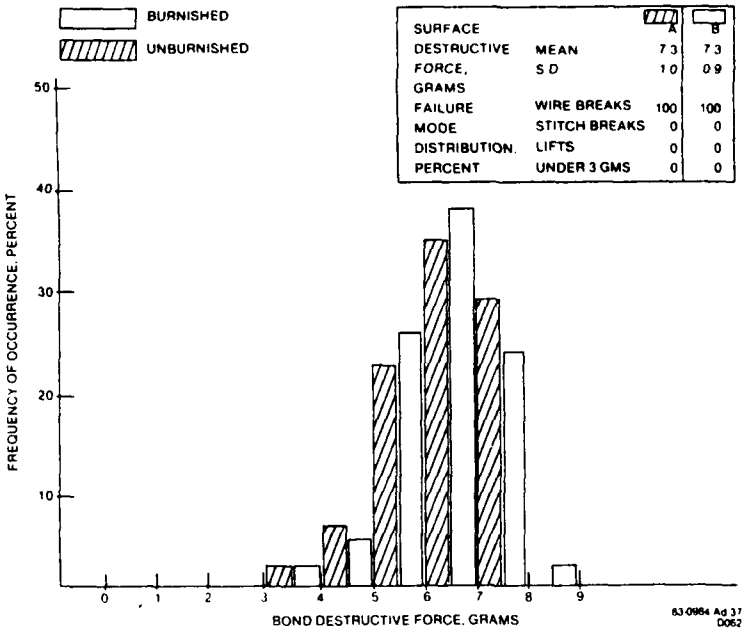


Figure 37. Distribution of bond strengths, thermocompression bonds to TFS 3045 Au.

TABLE 24. WIRE BOND PULL TEST RESULTS. TFS 3045 GOLD ON PES SUBSTRATES

Parameters	Results According To Bonding Method					
	TS	TS	TS	TS	TC	TC
Substrate temperature (°C)	150	150	150	150	235	235
Surface	B	A	B	B	B	A
Number bonds	105	25	77	50	59	66
Mean destructive force (gm)	7.7	9.1	8.4	7.7	7.3	7.3
Standard deviation (gm)	1.7	1.7	1.5	2.1	0.9	1.0
Wire breaks (%)	0	48	29	46	100	100
Stitch breaks (%)	93	52	59	52	0	0
Ball or Stitch (%) lifts, (%)	7	0	12	2	0	0
Under 3 gm (%)	5	0	0	4	0	0

4.3.4.3.2 Cermalloy 4350 and Plessey C5800

Sample substrates with patterns printed in Cermalloy 4350 gold and Plessey EMD C5800 were provided by the vendor. Both are on Alpha substrates, and were fired at 625°C. The pattern consisted of a meandering line approximately 20 mils wide, crossing back and forth across the substrate.

The results of thermosonic bond testing on two Cermalloy and one Plessey samples are shown in table 25.

The results of testing the C5800 were especially impressive when compared to results on high temperature films on alumina. Pull strength distributions, seen in figures 38 and 39, were tight, and no low-value failures occurred. The only negative feature was the difficulty in making satisfactory stitch bonds to the Cermalloy 4350. Large percentages of the breaks involved partial lifts at the stitch. It was felt that this problem could be reduced with more optimization.

TABLE 25. WIRE BOND PULL TEST RESULTS FOR GOLD THICK FILM FIRED AT 625°C, THERMOSONIC-BOND, 1-MIL GOLD WIRE

Bond type[a]	Quantity	Treatment[b]	Destructive force[c] (gm)		Failure mode distribution (%)			
			Mean	SD	Wire	Stitch	Lifts	Under 3 gm
Cermalloy 4350	54	A	9.0	1.3	39	61[b]	0	0
Cermalloy 4350	65	B	8.1	1.4	25	75[b]	0	0
Plessey-EMD C5800	116	B	9.6	1.1	54	46	0	0

a. See Table 16 for code b. Partial breaks and partial lifts.

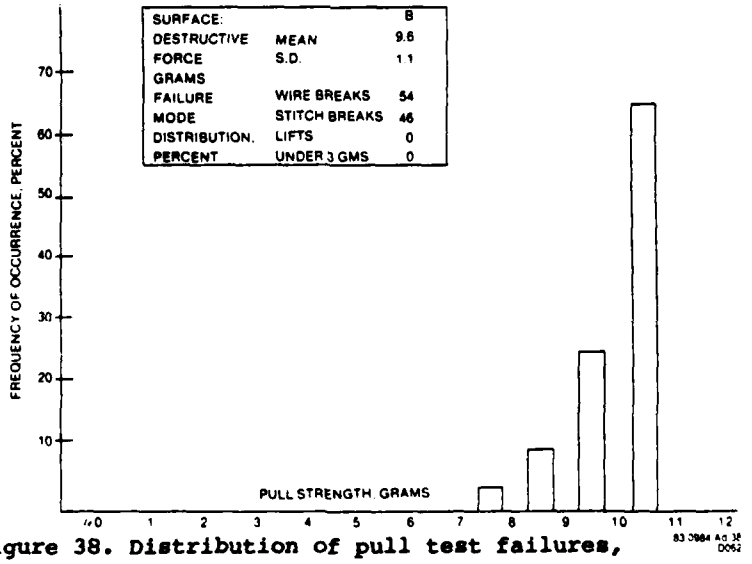


Figure 38. Distribution of pull test failures, thermosonic bonds, Cermalloy/EMD C5800 Au.

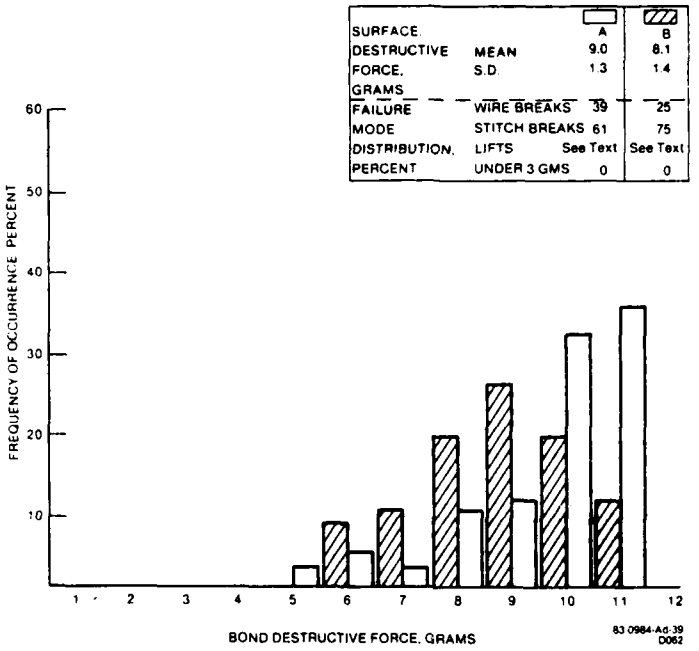


Figure 39. Distribution of pull test failures, thermosonic bonds, Cermalloy 4350 Au.

4.3.4.4 Analysis of Wire Bonding Problems

It was hypothesized that the gold films used in this program differed from high temperature gold films on alumina in two ways. First, the gold powder particles were not sintering to the degree observed in high-temperature films, resulting in lower cohesive strength. Thus, the portion of film to which the wire is bonded tends to separate easily from the main body of the film. Second, the porcelain surface is composed primarily of glass. The surface of the gold film on porcelain could be much glassier and therefore more difficult to bond to than the surface of a conventional gold film.

These hypotheses were tested by performing two sets of experiments. The "sintering' hypothesis was tested by printing the wire bond test pattern using TFS 3045 on two groups of alumina substrates. One group was fired at 600°C, and the other group at 850°C. Wire bonding tests were performed as before on both groups. In addition, the resistivity of samples of each group were measured, and SEM analysis was performed on each type of film. The "high glass content" hypothesis was checked by over-printing samples of low-temperature silver-bearing conductor and TFS 3045 gold with Cermalloy 4300 UF (an "unfluxed," or glassless, gold ink). When fired, the additional gold powder created a highly metallic surface for bonding.

4.3.4.4.1 Effect of Sintering

The sintering hypothesis was tested by printing the wire bond test pattern with TFS 3045 on two groups of alumina substrates. One group was fired at 600°C, the other group at 850°C. Wire bondability tests and Scanning Electron Micrograph (SEM) analyses were performed on substrates from each group. SEM's were also made on PE Substrates with Dupont 7711 PdAg fired at 600° and 675°C to observe sintering at temperatures within the range typically used for these materials.

Figures 40a and b show TFS 3045 gold on alumina fired at 600°C and 850°C, respectively. Considerably more sintering and grain growth has taken place at 850°C. The film fired at 600°C still shows much of the original particle configuration. Figures 41a and b show the palladium-silvers fired at 600°C and 675°C, respectively. The film fired at 600°C shows almost no sintering, which undoubtedly accounts for the poor solder adhesion measured previously. In the SEM of the film fired at 675°C, it is not possible to tell the extent of the sintering. It has the appearance of metal particles completely surrounded by a smooth, glassy, medium. This material is likely to be porcelain, although that has not been established.

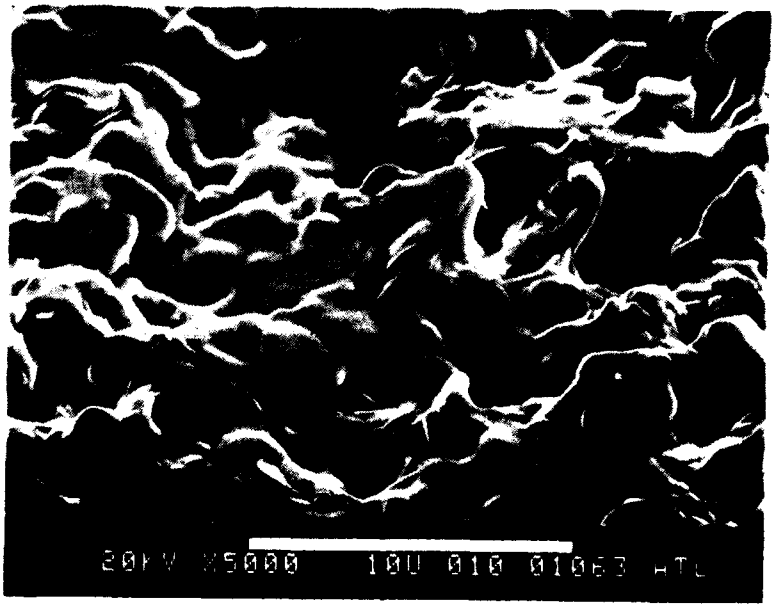


Figure 40a. TFS 3045 fired at 600°C on alumina. Magnification 5000x.

Figure 40b. TFS 3045 fired at 850°C on alumina. Magnification 5000x.

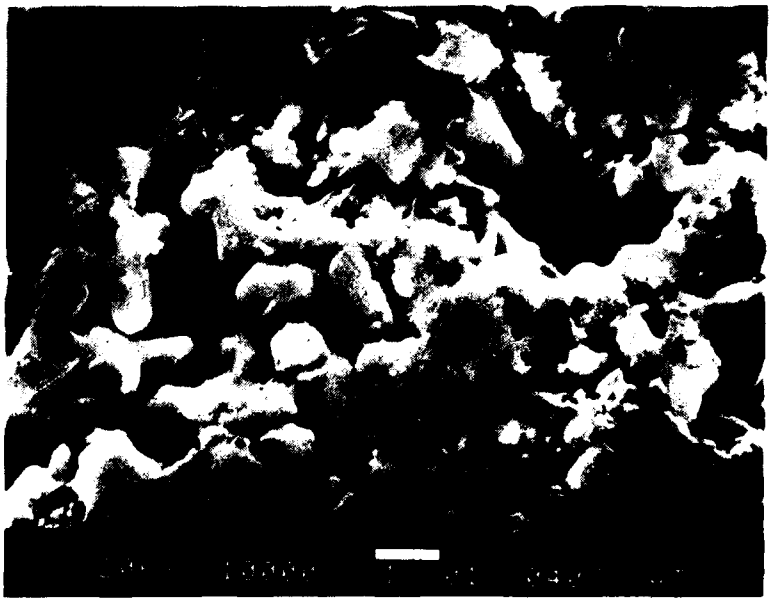


Figure 41a. DP 7711 Pd Ag fired at 600°C on PES. Magnification 10,000x.

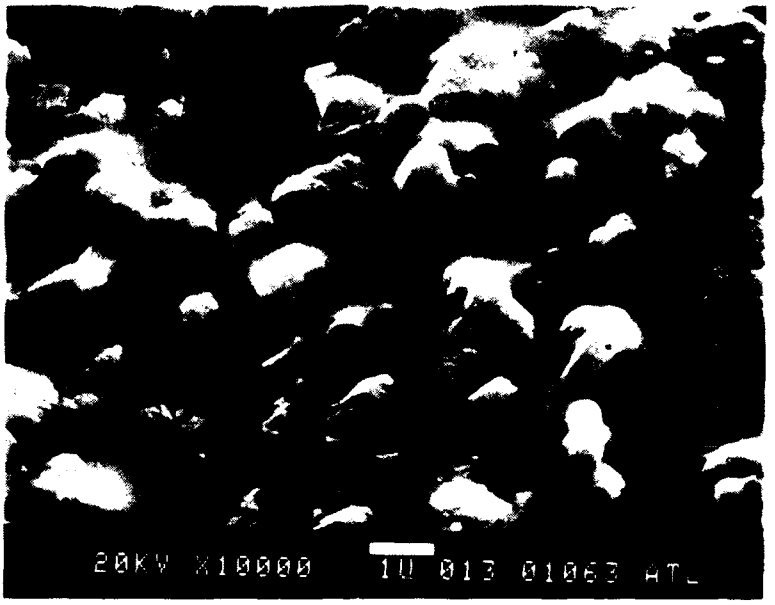


Figure 41b. DP 7711 Pd Ag fired at 675°C on PES. Magnification 10,000x.

Table 26 and figure 42 summarize results obtained on alumina substrates. Increasing the firing temperature from 600°C to 850°C dramatically improved the results. The failure mode changed from 100-percent stitch lifts to 100-percent wire breaks. The mean breaking strength increased by 25 percent, and the deviation about the mean decreased from 1.3 to 0.5 gr. In contrast, the results obtained on alumina fired at 600°C are generally similar to those obtained on PES as shown in figure 43.

No significant improvement occurred. Indeed, the PES failure modes included isgnificant percentages of wire breaks, where as all failures on alumina fired at 600°C wore stitch lifts.

Time did not permit further investigation of the effect of temperature on wire bondability of films on PES substrates alone. Later, substrates made in the pilot run were fired at 650°C, based on the results obtained here.

TABLE 26. WIRE BOND PULL TEST RESULTS, TFS 3045 GOLD ON ALUMINA SUBSTRATES, 1-MIL GOLD WIRE

Substrate Firing Temperature (°C)	Bonding Method	Quantity	Surface	Destructive Force (gm) Mean	SD	Failure Mode Distribution (%) Wire Breaks	Stitch Breaks	Lifts	Under 3 gm
600	TS	105	B	8.3	1.3	0	0	100	1
850	TS	105	B	10.5	0.5	65	35	0	0
600	TC	125	B	7.2	1.4	0	100	0	0
850	TC	60	A	8.4	0.8	100	0	0	0
850	TC	66	B	8.3	0.8	100	0	0	0

a. See Table 16 for code

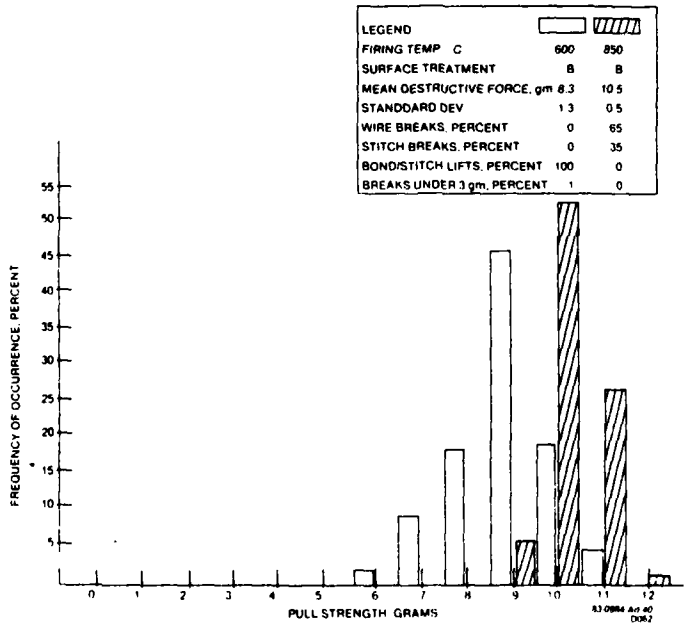


Figure 42. Effect of substrate firing temperature on wire bondability of TFS 3045 alumina substrates.

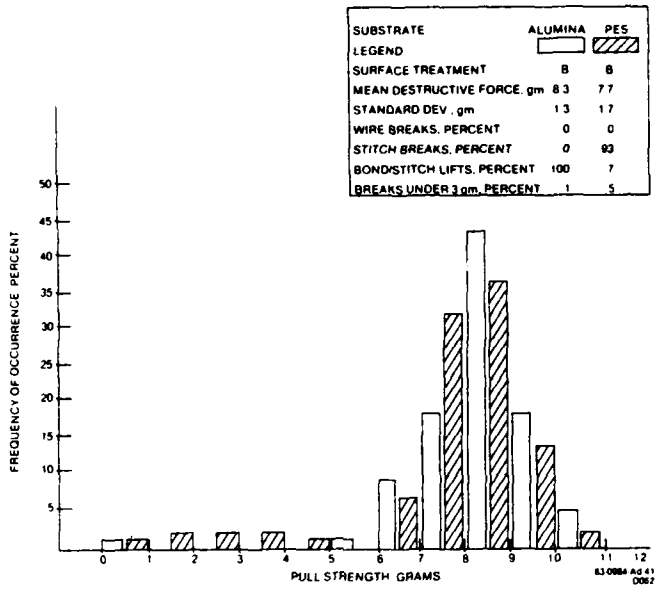


Figure 43. Comparison of wirebondability of TFS 3045 on alumina and PES substrates.

4.3.4.4.2 Effect of Increased Metal-Glass Ratio

In order to obtain a more metallic surface to improve wire bondability, a number of substrates with test patterns already printed with one of the conductors under study were over-printed with Cermalloy 4300 UF (an "unfluxed", or glassless, gold). Samples were prepared in which the underlying conductor had been fired previously, and others were prepared in which the underlying conductor was unfired.

Table 27 shows the results obtained with Cermalloy 4300 UF printed over several silver-bearing inks. Although the sample size was small, it is evident that overprinting with unfluxed gold resulted in greatly improved wirebondability.

Results obtained with both a separately fired and cofired samples of TFS 3045 over printed with Cermalloy 4300 are shown in figure 44. Again, a significant improvement was achieved over the performance of the single-phase film.

The results of this effort strongly indicate that the high glass content of conductor films on PES substrates contributes significantly to wire bondability problems. One method of increasing the metal content, over-printing with an unfluxed ink, substantially improved wire bondability.

TABLE 27. WIRE BOND PULL TEST RESULTS, SILVER-BEARING CONDUCTORS OVERPRINTED WITH CERMALLOY 4300 UF.

Bottom conductor	Quantity	Destructive force (gm)		Failure mode distribution (%)			
		Mean	SD	Wire breaks	Stitch breaks	Lifts	Under 3 gm
DP 7712, fired	10	8.9	0.8	90	10	0	0
DP 7713, fired	10	9.3	0.6	100	0	0	0
ESL 9694, fired	10	9.5	0.6	100	0	0	0
TFS 3347, fired	10	9.2	0.7	100	0	0	0
TFS 3418, fired	10	9.3	0.9	100	0	0	0

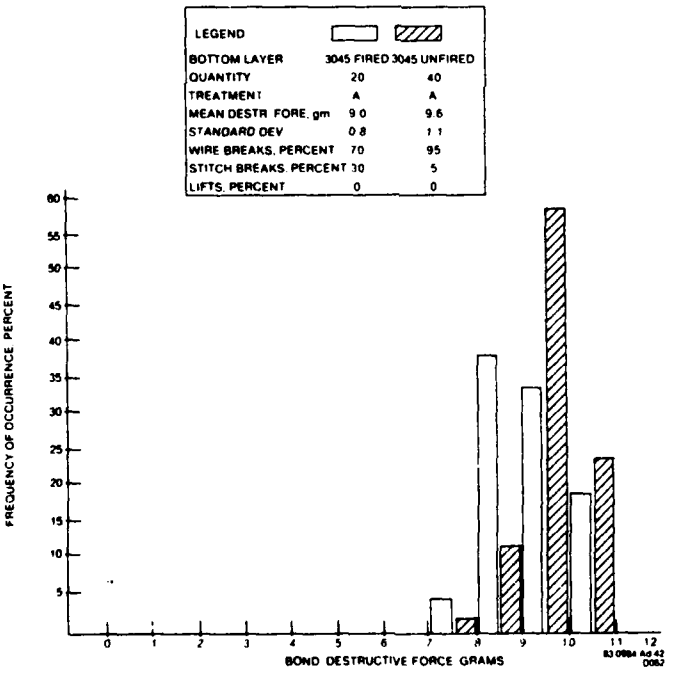


Figure 44. Wirebond pull test results, TFS 3045 overprinted with cermalloy 4300 UF.

4.3.4.5 Aging of TFS 3045

Several hundred bonds were made on TFS 3045 patterns on ECA and GE substrates for aging effect studies. Thermosonic bonding was used for all tests. Destructive pull tests were performed initially and after 100 hours and 400 hours at 125°C in air.

Results of the tests are depicted in figures 45 and 46 for ECA substrates and 47 and 48 for GE substrates. Table 28 summarizes the failure mode distribution for each segment of the tests; i.e., the relative numbers of wire breaks, stitch breaks, and lifts.

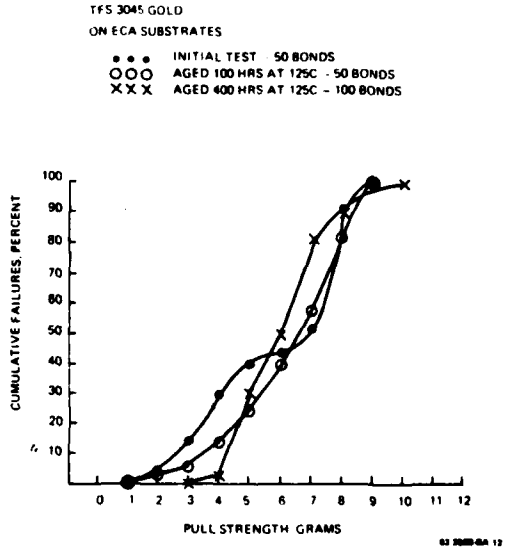


Figure 45. Effect of thermal aging on wire bond failure strengths. ECA substrates.

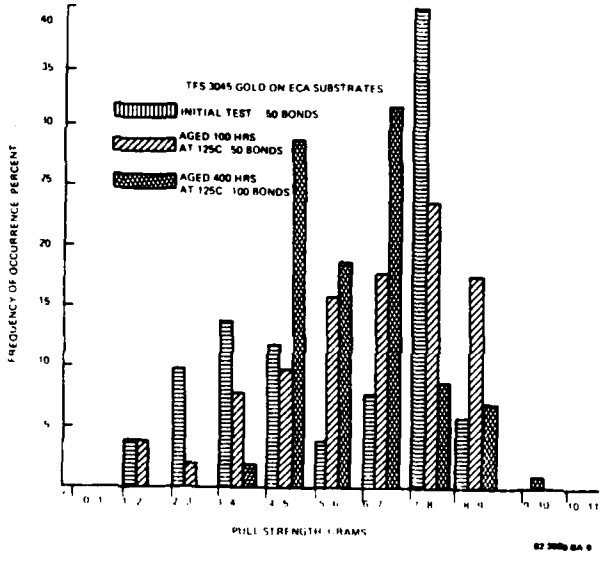


Figure 46. Distributions of bond failure strengths as a result of thermal aging. ECA substrates.

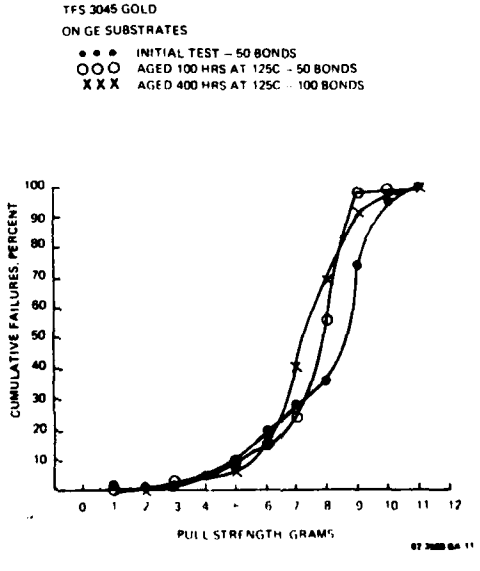


Figure 47. Effect of thermal aging on wire bond failure strengths. GE substrates.

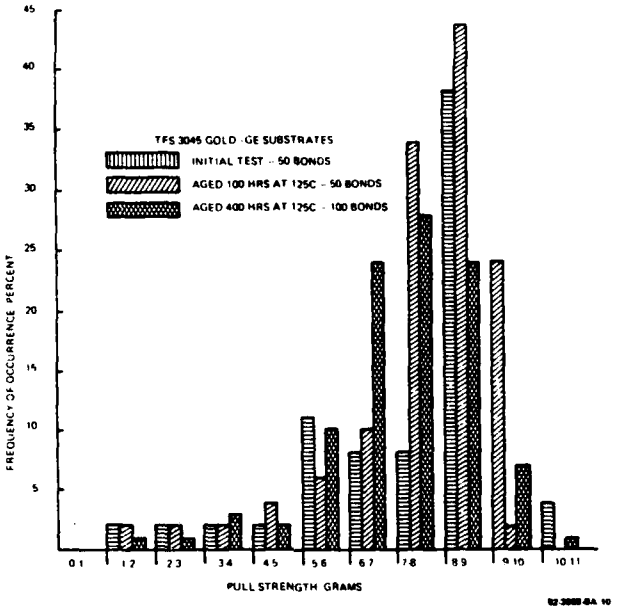


Figure 48. *Distribution of bond failure strengths as a result of thermal aging. GE substrates.*

TABLE 28. FAILURE MODES OF THERMOSONIC BONDS ON TFS 3045 GOLD

Time at 125°C (hours)	Failure mode distribution (percentage)							
	Wire breaks		Stitch breaks		Lifts		Under 3 gm	
	ECA	GE	ECA	GE	ECA	GE	ECA	GE
0	38	46	56	52	6	2	14	4
100	30	54	60	46	10	0	8	6
400	1	1	99	93	0	2	0	2

The destructive pull strengths of the bonds did not change significantly over the 400 hours of aging. However, for both ECA and GE substrates, the percentage of stitch breaks increased dramatically between 100 and 400 hours. This may have been caused by the effect of temperature on the hardness of the gold wire. The number of bond lifts decreased for the ECA substrates, and remained essentially constant for the GE.

These tests tend to show that gold wire bonds to gold thick film on PES substrates are virtually unaffected by 125°C aging for up to 400 hours.

4.4 RESISTORS

Resistor material evaluations were intended to discern the limits of PES technology with regard to resistor performance, to determine process capabilities and optimum processing conditions for these materials and to outline the changes necessary to convert a manufacturing line from alumina-based resistor processing to PES. While several vendors inks were evaluated and selections were made for use in pilot line production, this portion of the program was not designed as a vendor evaluation.

Throughout the testing, consideration was given to the requirements of high-volume processing and to the use of available materials. For this reason, most of the fired property testing done on thick-film pastes was done on ECA substrates, which are currently more readily available than the functionally similar substrates available from GE.

4.4.1 Materials and Tests

During the initial stages of the project, vendors that provide thick film pastes for use on alumina were contacted and literature was obtained from each concerning PES-compatible materials. Review of this literature revealed that only two of the responding vendors, Dupont and ESL, provided pastes with the full range of resistivities (10 ohm/sq to 1 Mohm/sq) required to meet typical ordnance hybrid applications. A third vendor, TFS, provided pastes with

resistivities between 10 ohm/sq and 100 k ohm/sq. On this basis materials from these three vendors, listed in table 29, were selected for evaluation.

Fifty grams of each of the pastes listed were purchased for use in the evaluation. Each material was then examined by testing each of the properties listed below.

- o Viscosity--Using Brookfield HBT Viscometer and SC4-14/6 sample chamber at 25 ± 0.5°C. Testing was done over the 0.4 to 40 range of shear rates
- o Percent solvent and percent solids
- o Print thickness
- o Sheet resistivity as a function of
  - Geometry: 0.2 to 5 square, 0.040 to 0.080 in. width
  - Firing temperature: ±25°C from nominal
  - Substrate vendor: ECA and GE
- o Repeatability
- o Trimmed and untrimmed stability
- o Compatibility with PES substrates

Fired property testing was performed on test samples fabricated using the test pattern shown in figure 49. This pattern contains resistors of between 0.2 and 5 squares over 20, 40, and 80 mil widths for use in the evaluation of the effect of geometry on resistivity. Also, the pattern is designed so that 40-mil-wide resistors are printed with terminations both parallel and perpendicular to squeegee motion. For each paste, conductor patterns were prepared using pastes and processing parameters specified by the vendor. Samples were fabricated using screen and printer setup parameters selected to produce the dried print thicknesses within the ranges specified by the vendor for such paste. Thicknesses were optimized for geometries similar to those found on the

Table 29. RESISTOR MATERIALS EVALUATED

Vendor	Product line	Range of resistivities
Electro Science Laboratories Incorporated (ESL) 2211 Sherman Avenue Pennsauken, NJ 08110	3100 Series	10 to 10^6
Dupont Electronic Materials Division Wilmington, DE 19898	7600 Series	15 to 10^6
Thick Film Systems Division (TFS) Ferro Corporation 324 Palm Avenue Sant Barbara, CA 93101	600 Series	10 to 10^5

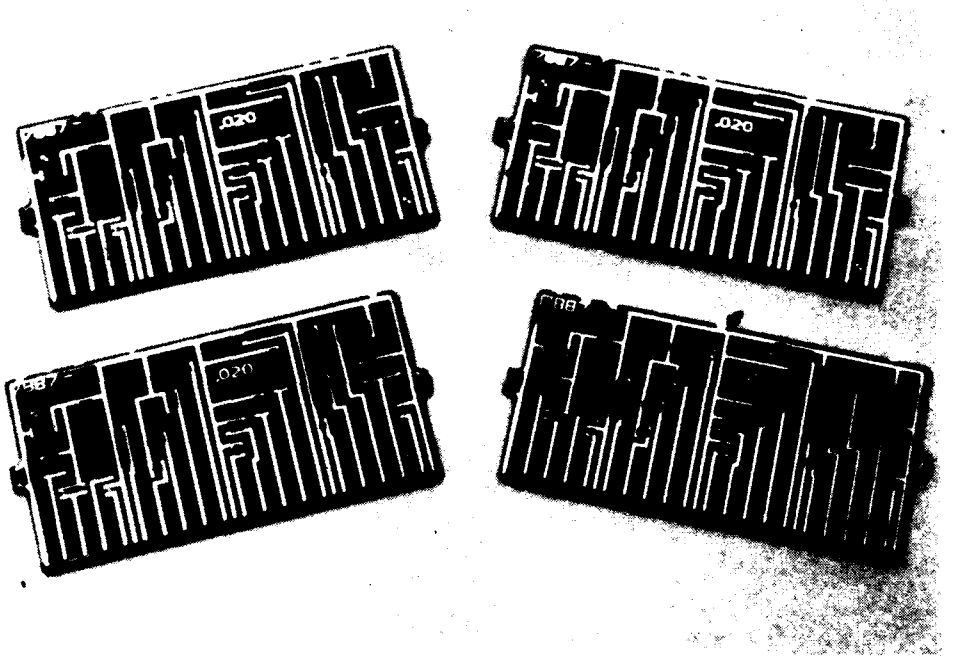


Figure 49. Resistor test pattern.

pilot line circuit to be discussed later. Drying and nominal firing parameters were also as recommended by the vendor. All tests examining as-fired resistivity were based on a sample of eight substrates. Laser trimming and stability testing will be detailed in section 4.4.2.4 and 4.4.3.

4.4.2 Results

While detailed testing results are listed for each paste tested, it was not the intent of the program to evaluate ink systems or vendor performance. Discussion will focus on those critical process areas that the evaluation identified as significantly different from conventional processing on alumina.

The viscosity and percent solids for each of the pastes is listed in table 30. These properties were within the vendor specification for each paste and were similar to those of resistor pastes fabricated for use on alumina. The range of dried print thickness obtained was not significantly different from resistor pastes fabricated for use on alumina.

TABLE 30. RESISTOR MATERIALS--PASTE PROPERTIES

Material designation	Nominal resistivity (ohms/sq)	Viscosity, centipoise [a]	Fired percent solids
DP 7611	15	110	78
7621	100	100	76
7631	1k	110	75
7641	10k	120	70
7651	100k	120	66
7661	1M	120	67
TFS 600-101	10	170	64
600-102	100	160	61
600-103	1k	350	61
600-104	10k	230	62
600-105	100k	230	64
ESL 3111	10	160	74
3112	100	190	70
3113	1k	150	73
3114	10k	140	73
3115	100k	200	72
3116	1M	215	68

(a) Measured at 10 rpm, Brookfield HBT Viscometer SC4-14/6 Cup and Spindle.

4.4.2.1 Resistivity and Repeatability

The as-fired sheet resistivity for each paste fired at the vendor's nominal temperature is given in table 31.

For each paste the mean sheet resistivity and standard deviation over all the resistor geometries on the test pattern is reported, as well as the range of the standard deviations calculated for each resistor geometry. Because the overall standard deviation for the paste represents the variation between geometries as well as the variation within each geometry (repeatability), comparing it to the range of individual standard deviations produces an overall assessment of the geometric sensitivity.

Nearness to nominal value of the paste as received from the vendor is not a critical parameter for paste use. Paste blending makes any value between the highest and lowest pastes of a vendor series easily obtainable. However, comparing results from a vendor's quality assurance department with evaluation results gives an indirect measure of the process sensitivity of a paste, and

comparisons of observed resistivities across the range available in a given paste series provide an indication of the vendor's control over the manufacturing process.

All three vendors' pastes had resistivities higher than nominal for the lowest resistivity pastes, and generally lower than nominal value for higher (> 10 kohm/sq) sheet resistivities. ESL materials were closest to nominal across the range of pastes; DuPont pastes had the greatest spread in values. When allowance is made for differences between vendor test geometries (generally 0.040 in. widths and aspect ratios up to 2 squares) and the complexities of the resistor testing process (termination effects, thickness variation printing techniques) are considered, then the observed variation in as-fired resistivities is not surprising. Westinghouse experience with pastes from a variety of vendors for use on alumina indicates that the values listed in table 31 are well within the expected range for these pastes.

The repeatability of the resistance values as measured by standard deviation varied widely from paste to paste and from vendor to vendor. In high-volume use, repeatable materials are essential for high-yield, cost-effective production. As such, this parameter was weighed heavily when considering pastes for pilot line use. ESL pastes had the tightest distributions, followed by TFS and DuPont, with the exception of the 100k pastes. The range of test results was similar to that for resistor pastes on alumina. The low-resistivity pastes from each of the three vendors had distributions with standard deviations greater than 60 percent for some geometries. More extensive experimentation would be required to determine the cause of this behavior. Fortunately, the circuit chosen for pilot line testing did not require the use of pastes with resistivities lower than 2 kohm/sq.

TABLE 31. RESISTOR MATERIALS--SHEET RESISTIVITY

Paste Type	Sheet resistivity Mean[(a)]	Standard Deviation (SD)	Range of SD's for individual geometries
DP 7611	1.74	0.749	0.089 - 1.07
7621	1.77	0.376	0.070 - 0.578
7631	1.15	0.194	0.030 - 0.139
7641	.988	0.189	0.021 - 0.076
7651	.579	0.176	0.020 - 0.351
7661	.798	0.360	0.010 - 0.674
ESL 3111	1.23	0.345	0.044 - 0.688
3112	.956	0.068	0.015 - 0.062
3113	1.07	0.076	0.019 - 0.138
3114	.993	0.077	0.026 - 0.077
3115	.823	0.160	0.018 - 0.13
3116	.707	0.126	0.022 - 0.052
TFS 600-101	.99	0.196	0.024 - 0.631
600-102	1.08	0.160	0.049 - 0.169
600-103	1.95	0.376	0.051 - 0.194
600-104	1.19	0.114	0.022 - 0.117
600-105	.88	0.125	0.057 - 0.214

a. Nominal = 1

4.4.2.2 Effect of Geometry

Figures 50, 51, and 52 describe the behavior of each of the pastes as a function of aspect ratio for 0.020, .040, and .080 in. widths. While the curves tend to have positive slopes, the rate of increase, or change between given aspect ratios for any paste of family of pastes at any width, is very difficult to predict. This strong unpredictable variation with geometry (and also with direction of print) is very similar to the behavior of traditional thick films on alumina. A thick film production line based on alumina would have no special difficulty with converting to PES-based technology. The mechanisms for dealing with this unpredictability are already in place. The wide variations are caused by a strong dependence of resistivity on fired thickness, coupled with thickness variation and geometry due to the kinetics of the screen printing process; the interaction of the screen mesh and emulsion with the substrate; terminations; and squeegee edge during the print stroke.

While this behavior frequently requires substantial process flexibility on a low-volume custom application (such as military avionic hybrids), high-volume production (such as for ordnance) would be able to tailor materials, processes, and designs to maximize production efficiency.

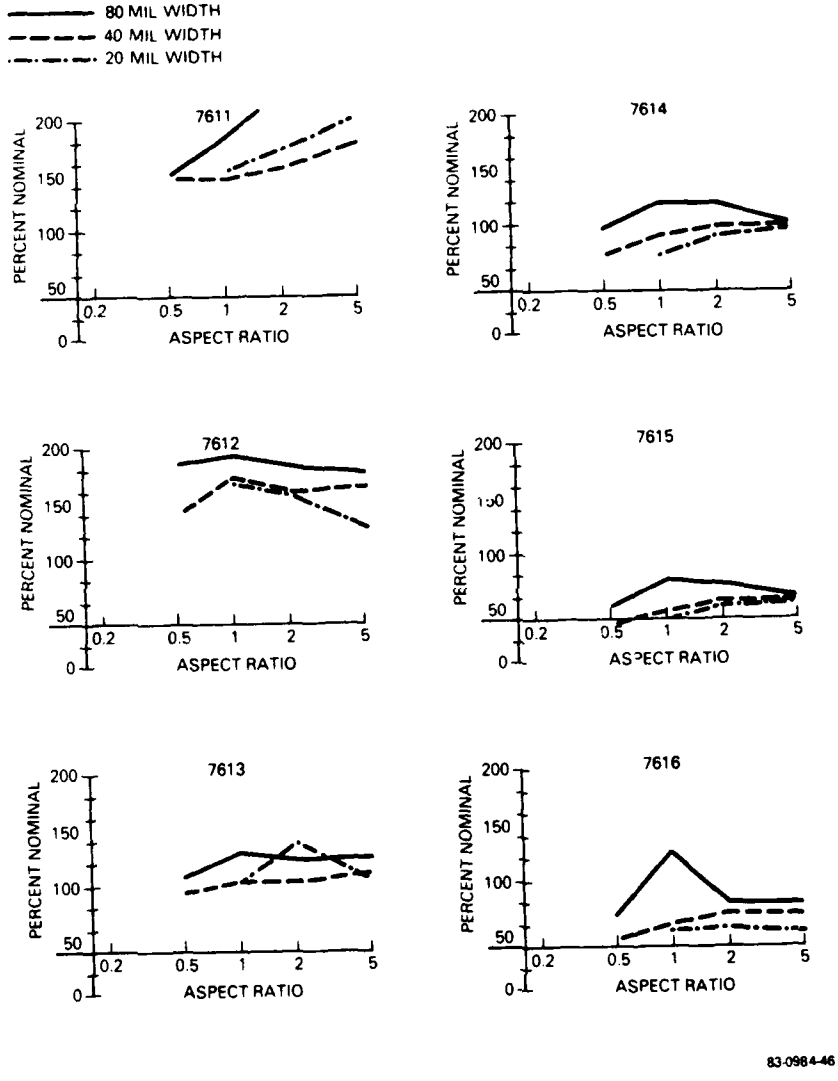


Figure 50. Variation of resistance with geometry for Dupont 7600 series resistor pastes.

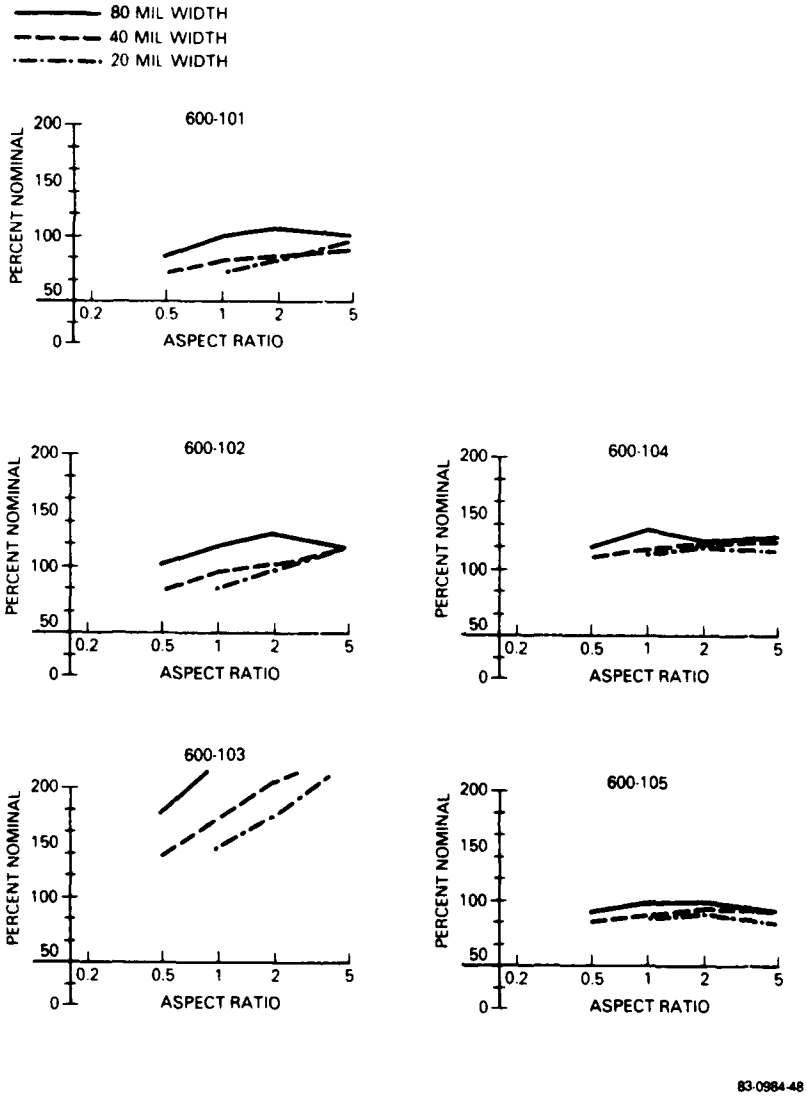


Figure 51. Variation of resistance with geometry for TFS 600 series resistor pastes.

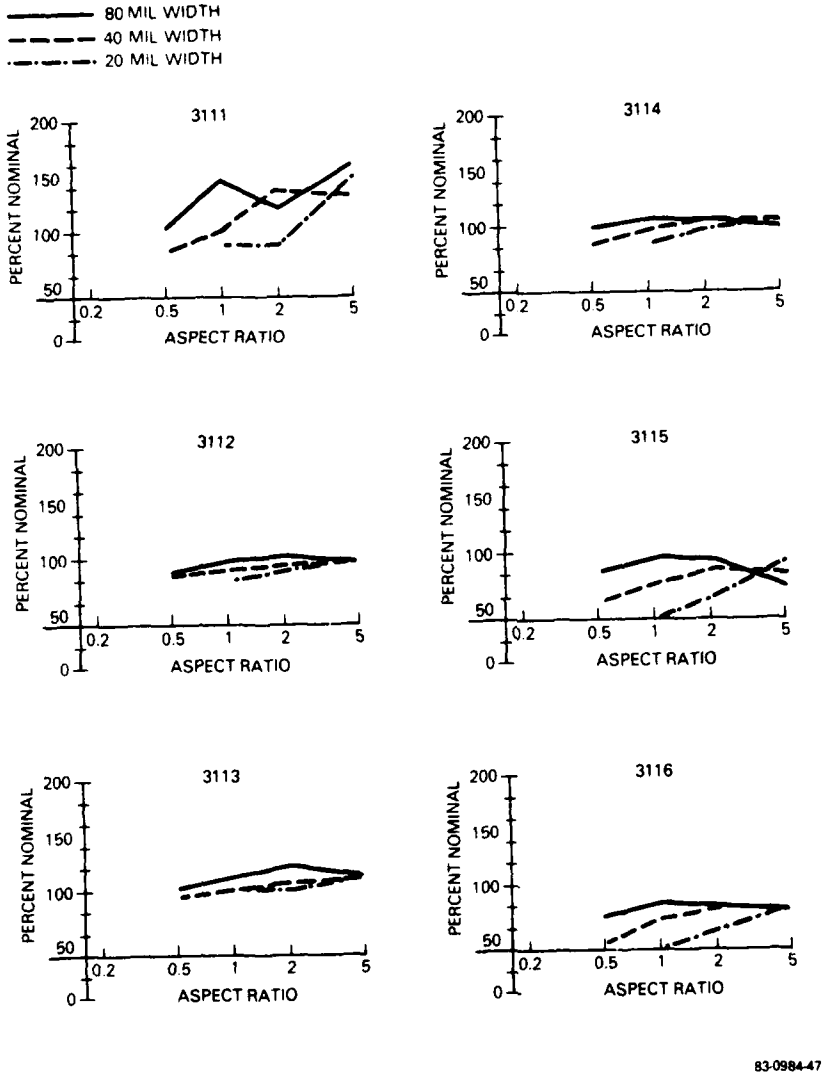


Figure 52. Variation of resistance with geometry
ESL 3100 series resistor pastes

4.4.2.3 Effect of Firing Temperature

The variation of resistivity with firing temperature was of special concern during the study. The long furnace runs of identical parts occuring during volume production dictate that the furnace temperature controlls will undergo numerous cycles during the run, causing temeratures to fluctuate. It is important that the allowable firing variation for each paste be understood so that furnace controls may be specified that will eliminate temperature fluctuations large enough to cause product losses. Also, earlier measurements (sect. 3.3.2.2) showed that, in most cases, nominal paste firing temperatures were above the softening points of the porcelain enamels used in substrate manufacture. The lowered viscosity of the glassy enamel would greatly enhance its chemical reactivity, potentially causing increased substrate/paste interaction. Conduction mechanisms which were dependent on these interactions would be highly dependent on firing temperature, in much the same way as earlier thick film resistor compositions based on ruthenium metal were sensitive to firing temperature because of the Ru/RuO_2 reaction.

The nominal firing temperatures and percentage of variation in mean resistivity of each paste as firing temperatures varied from 25°C below to 25°C above the nominal firing temperature are listed in table 32. In each case firing sensitivity increases as sheet resistivity increases, probably due to increased dependence on glass/oxide reactions for conduction in the glassier, high-resistivity pastes. The DuPont pastes were generally least sensitive to firing, followed by the TFS and ESL materials. The values listed are somewhat higher than the 150-percent worst case that is typical for conventional pastes formulated for firing at 850°C on alumina. This is probably due to the low solid-state reaction rates for the paste constituents at these low temperatures, making the development of almost all conduction mechanisms temperature dependent. The DuPont pastes, with the highest nominal firing temperature, have the lowest sensitivity.

The sensitivity shown by these materials, while higher than conventional inks, is still well within the range necessary for smooth production operation with available furnaces ($\pm$5°C at peak over weeks of operation); the lone exception is the ESL 3116 material (1 Mohm/sq) which exhibited an unusually strong firing sensitivity over the temperature range used. It is probable that one of the firing temperatures used was completely outside the range of this material, in which case the trial should be repeated using a narrower temperature range.

4.4.2.4 Stability

The likelihood of interaction with the substrate material is high for PES materials because the softening point of the substrate material was below the firing temperature of the resistor inks in most cases. Potentially these substrate/resistor interfaces could be both brittle and highly stressed, causing the formation and growth of microcracks during laser trimming. These microcracks could lead to long term resistor instability.

TABLE 32. RESISTOR MATERIALS--EFFECT OF FIRING TEMPERATURE

Paste type	Nominal firing temp (°C)	Change (%) $\left(\frac{(R_T - 25°C) - (R_T + 25°C)}{R_{To}} \times 100\right)$
DP 7611	650	8
7612	650	59
7613	650	0.9
7614	650	23.9
7615	650	62.7
7616	650	123
ESL 3111	625	-
3112	625	-18.5
3113	625	99.9
3114	625	121
3115	625	166
3116	625	199.5
TFS 600-101	600	129.9
102	600	-43.5
103	600	2.4
104	600	129
105	600	405

In order to assess the stability of resistors on PES, five of the resistor test substrates for each paste were selected and fired at the vendor's nominal temperature. After optimum trim parameters were determined (as discussed in sect. 4.4.3), 14 of the resistors on each substrate were trimmed. Resistors selected for trimming were all between 0.5 and 2.0 squares of .040 and .080 in. width. All were trimmed using a single plunge cut with kerf length equal to 50 percent of the designed resistor width. As soon as practical after trimming, the resistances of both the trimmed and untrimmed resistors were measured. Because it was necessary that all measurements be made on the same measurement system and production trimmer, time could not be allocated for additional measurements; thus, initial measurements were made on a separate system 3 to 5 minutes after trimming. The test samples were then stored at 150°C for 800 hrs. Periodically, they were withdrawn and resistance measurements taken on both the trimmed and untrimmed resistors. The results of these measurements are summarized in figures 53, 54, and 55.

The results indicate that the while average drift of each of the resistor materials was generally acceptable (less than 0.5 percent after 800 hr) the distribution of individual drifts was unacceptably high. The range of drifts frequently exceeded 4 percent and sometimes exceeded 7 percent. Trimming appeared to enhance resistor stability, as untrimmed resistors tended to drift more than identically processed trimmed resistors. This behavior was also reported by Allington et al.[3] Some variation between vendors was observed, with ESL drifting most, followed by DuPont, with TFS showing significantly less drift.

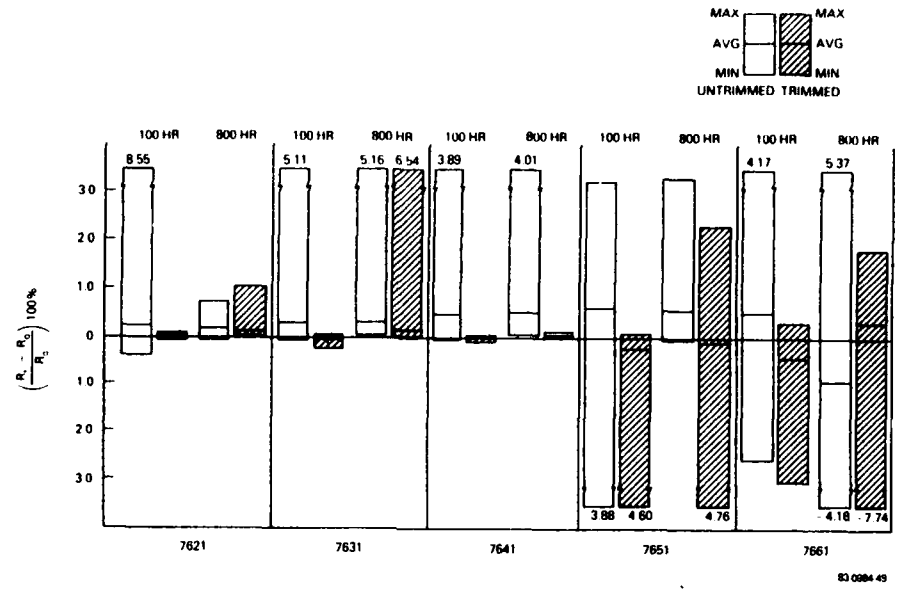


Figure 53. Long term stability, Dupont 7600 series.

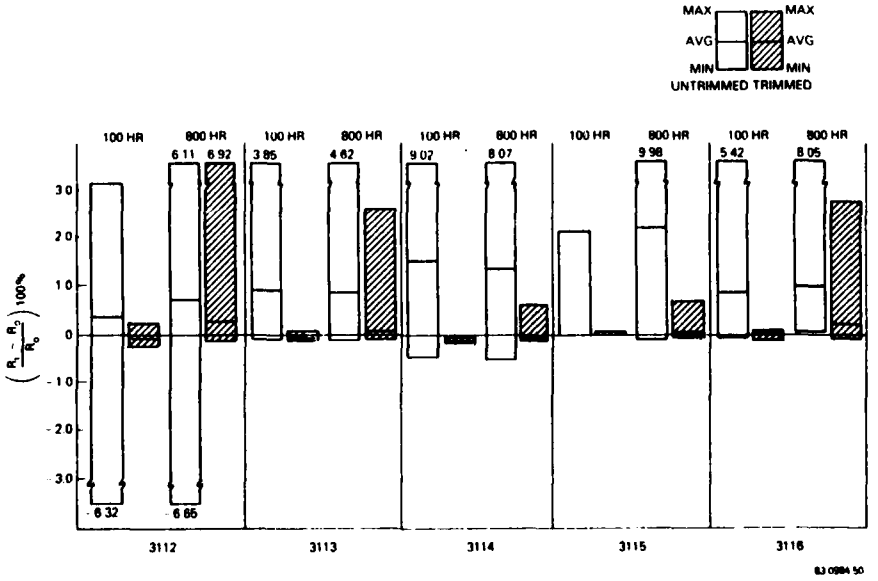


Figure 54. Long term stability, ESL 3100 series.

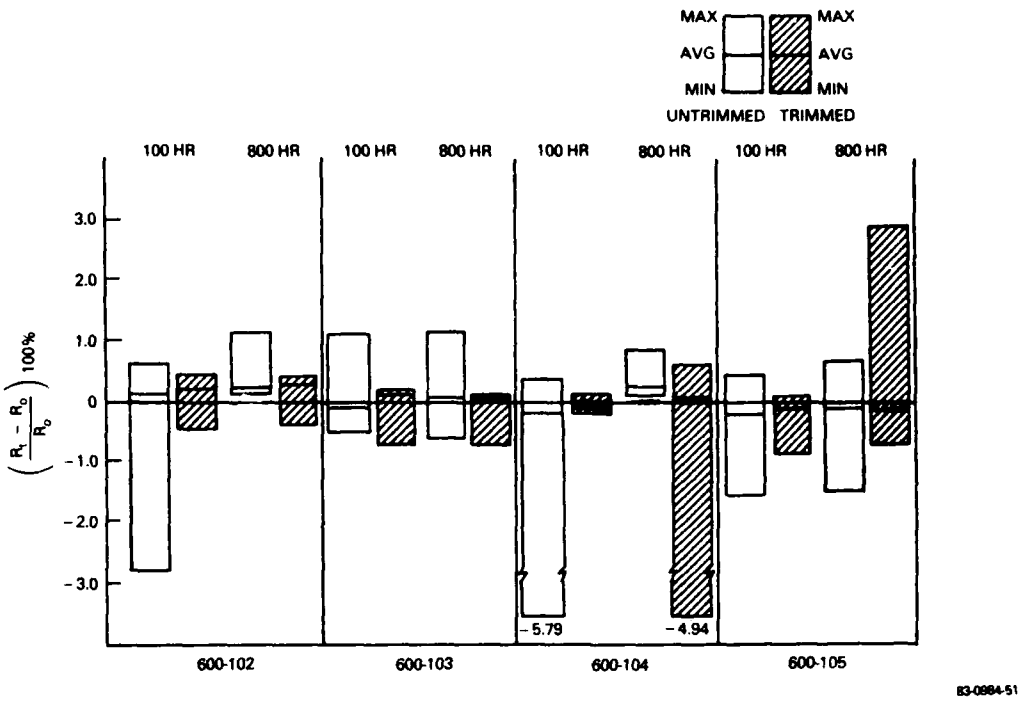


Figure 55. Long term stability, TFS 600 series.

While some of the wide range in recorded drift measurement can be related to inaccuracies obtained when making precise measurements on production equipment over a period of months, the consistency of the results as a function of trimming and vendor gives the data some validity. One possible mechanism for the observed behavior is the interaction between the porcelain substrate insulation and the resistor composite during firing. With both porcelain coating and resistor material being glass-based materials raised above their softening point during firing, the potential for interdiffusion is enhanced. This may give rise to the formation of a highly stressed interfacial layer during firing. The relief of these stresses would be poorly controlled and therefore unpredictable. Laser trimming may provide some stress relief and contribute to greater stability. This possibility is supported by the greater stability shown by the TFS pastes, which are fired at a lower temperature, at or below the softening point of the enamel. Obviously, more work is required to fully document and understand this behavior. However, based on these results, real concern exists as to the suitability of these materials for use where precise values are required.

4.4.3 Trimming--Special Problems

Because the resistor materials and the enamel coatings investigated here are similar in composition (oxide fillers in a glassy matrix) and color, there is relatively little difference in their material removal rates during laser trimming. In contrast, when trimming resistors screened and fired on alumina, significantly greater laser energy is required to penetrate the substrate than to vaporize the resistor. For this reason care must be taken when trimming resistors on PES to remove the resistor without boiling away the enamel, exposing the metal core and giving rise to shorting between the metal core and the resistor. Since the range of acceptable trim parameters including focal distance, bite size, Q-rate, and power is quite small, substrate flatness and thickness range over a lot of substrates must both be specified and controlled in a production operation.

In order to determine the optimum trim parameters for each substrate lot, scan cuts were made on 0.080-in.wide resistors using a matrix of setup parameters. Kerfs were then examined optically at 100x for removal of resistor material and damage to the enamel coating. Kerfs were judged acceptable if the resistor was completely removed, leaving a clean kerf, without causing boiling and cracking in the underlying porcelain. After optimum parameters had been determined in this manner, cuts were made at various points over the substrate length, and kerfs were again examined to determine the effect of substrate flatness. Routine trimming was impossible on lots of substrates which exhibited excessive bowing. Substrates prepared by lapping the enamel flat before thick film processing eliminated this problem, but the extra processing would significantly increase substrates costs and the thinner enamel coating would make the acceptable laser parameter ranges smaller.

Fortunately, samples fabricated using ECA substrates were sufficiently flat that trimming could be done over the entire substrate without laser adjustment. However, the potential for problems related to flatness may limit the size of substrates that may be processed in volume with resistors, undermining one of the real advantages offered by PES technology.

4.5 Dielectrics

Thick film dielectric paste materials have extremely stringent use requirements, especially for multilayer applications. The printing, drying, and firing operations must yield a coating that can reflow sufficiently to close any pinholes and voids left by the printing operation, yet does not fill vias required for interlayer connections, nor spread to cover nearby conductors such as wirebonding pads. Additionally, the resulting insulating layer must have acceptable dielectric properties. Because the rheological properties of dielectric functional materials are different from conductors or resistors, dielectric paste technology frequently matures at a slower rate.

Dielectric testing for this program was limited to examining the potential of existing materials as crossover patch dielectric in resistor bearing substrates (such as the M734 amplifier). However, because the test patterns selected also provide for examination of properties such as via resolution, some inference of suitability for multilayer application can be made.

4.5.1 Tests and Results

After product literature review and discussion with paste vendors, four dielectric pastes, listed in table 33, were selected for evaluation.

A test pattern was selected which provided the circuit configurations necessary to measure the integrity of the dielectric layer (degree of pinholing), dielectric properties listed above, via resolution between 0.020 and 0.010 in., compatibility of the dielectric layer with the substrate and conductor materials, adhesion of the dielectric, and dielectric print thickness. This test pattern (9RD4135C) is shown in figure 56.

For each material evaluated, five test substrates were fabricated. A single printing, drying, and firing of a compatible conductor was followed by two separately fired dielectric layers. Screen printing parameters were selected so as to produce the fired thickness recommended by the paste vendor. Firing was at the vendor-recommended profiles. Following dielectric processing a top layer of TFS 3045 gold was printed and fired. This material was chosen as the top layer because, during pilot line production, crossover conductors were to be printed on the same layer as Au wirebonding sites. Wirebonding studies had indicated that a gold material would be required to maximize wirebondability and wirebond integrity.

After fabrication the substrates were examined for evidence of substrate/dielectric incompatibility, and dielectric thickness (double layer) was measured using a profilometer. The number of closed vias (0.020, 0.015, and 0.010 in.) was determined microscopically with a minimum of 0.004 in. of exposed underlaying conductor required for acceptance. Adhesion (tape test) was measured, followed by dielectric constant, dissipation factor, conductance, and bulk resistivity measurements at 1 kHz. Isolation testing at 12 V was performed, and the number of shorted lines and shorted capacitors was noted. These results are summarized in table 33.

The results indicate that none of the materials evaluated was better than marginally acceptable. All the materials, except the EMCA 9041-1 exhibited an unacceptable tendency to form pinhole-related shorts. In order to produce reliable crossovers routinely in volume production, 100% isolation is required at the testing level performed. While the EMCA 9041-1 produced acceptable isolation, the material tended to separate between the two dielectric layers during adhesion testing. In the case of the DuPont and ESL materials, shorting was so severe as to make dielectric property measurement impractical. No evidence of substrate/dielectric incompatibility was found and, when measurement was possible, electrical properties were comparable to thick film dielectric materials used on alumina. It is likely that further processing work, particularly increasing the fired dielectric thickness and altering drying/firing schedules would eliminate the above failure modes. However, this investigation indicates that processing windows are likely to be small and more material investigations are indicated.

TABLE 33. DIELECTRIC PASTE EVALUATED AND TEST RESULTS

Material	Compatibility	Thickness (in.)	Adhesion	Isolation % Passed Capacitors	Isolation % Passed Lines	Vias open %	K	Tan (δ)	Resistivity (Ω cmx10^{12})
TFS 1120TCG	A	0.0015	A	96	85	98.8	7.8	0.001	2.45
DuPont 7701	A	0.0022	A	95.3	70	100	*	*	*
EMCA 9041-1	A	0.0017	U	100	100	99	8.3	.003	80
ESL M4030	A	0.0011	A	43.5	25	100	*	*	*

U Unacceptable

A Acceptable

* Testing halted

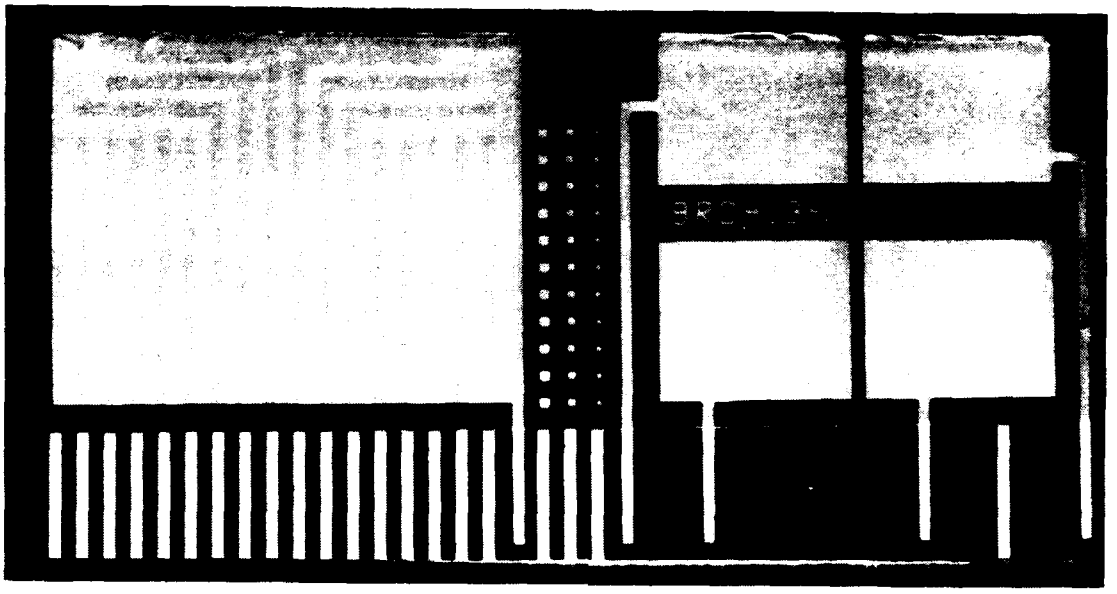


Figure 56. Dielectric ink test pattern.

4.6 PACKAGING

4.6.1 Background

One of the principal areas of concern in the use of IMS for ordnance hybrids is "packaging." Packaging, as applied to hybrid microelectronics, includes all those elements of construction of a component or assembly necessary to permit it to survive and function as planned in the environment expected to be seen during test, storage, and use. For the devices of concern to this program, the environment includes exceptionally high mechanical shock and acceleration. Packaging includes chip attachment, encapsulation, molding, shielding, electrical interconnection, protective covering, and mounting to support structures.

Each of these elements of packaging involves an interaction between two or more contiguous parts under varying conditions of temperature, atmosphere, and movement. Part of the task of bringing a new substrate technology into use for ordnance hybrids is to develop a packaging technology compatible with the new substrates, since a new complex of interactions begins to operate. In some cases, new processes and materials must be employed. A second aspect of the task is to identify ways in which the new substrate material can be used to advantage, i.e., to simplify or otherwise improve the overall packaging problem.

In the test program planned for this task, these two parts of the problem were addressed. First, the applicability of many techniques used for ceramic-based hybrids were evaluated. Interconnection, solderability, bonding materials and techniques, and environmental protection of porcelain-enameled steel hybrids were tested. Second, the feasibility of core metal-insulating layer combinations other than porcelain enamel and low-carbon steel were investigated. The details of the test plan are given in the following sections.

4.6.2 Evaluation Plan

The test program followed for the Packaging Evaluation phase is summarized in table 34. It was planned to divide the program into two segments. In one segment, chips (tantalum capacitor, ceramic capacitor, and silicon integrated circuit) were mounted on test substrates purposely designed for this purpose. Chips were mounted using each of the several conventional chip-mounting methods. The assemblies were tested, then subjected to a typical Mil-Std-883B environmental stress cycle for military hybrids, as shown in table 35. At the completion of the cycle, the assemblies were given a careful visual examination and retested.

TABLE 34. PACKAGING EVALUATION PLAN

Operations	Test	Method
1. Epoxy chip mount	Shear	Mil-Std-883B-2019
2. Solder ceramic cap	Shear	2019
	Environmental stress	See Table 35
	Centrifuge	2001.2 Cond B.
3. Solder tantalum cap	Environmental stress	Table 36
	Centrifuge	2001.2 Cond. B
4. Fabricate mock-up M734 fuze amplifier	Temperature shock	Table 35
	Temperature cycle	Table 36

TABLE 35. TEST PLAN DETAILS--PACKAGING EVALUATION

Test	Sample size	Test conditions
Push-off	4 substrates, 5 chips per substrate	
Thermal shock	4	15 cycles, 0 to 100°C
Temperature cycle	4	10 cycles, -55°C to +125°C
Bake	4	168 hours at 125°C
Constant acceleration	4	Centrifuge, 10,000 g, 1 minute
Push-off	As above	

The second segment of the packaging evaluation dealt with the effect of assembly on PES hybrids. Prior to the pilot production phase of the overall program, five M734-Fuze amplifiers were assembled to ensure that a PES hybrid circuit could withstand a sequence of soldering operations, epoxy operations, and wirebonding without apparent detriment to its reliability. The amplifiers were built completely and subjected to the testing shown in table 36. These models were not electrically functional, but were physically equivalent to functional units.

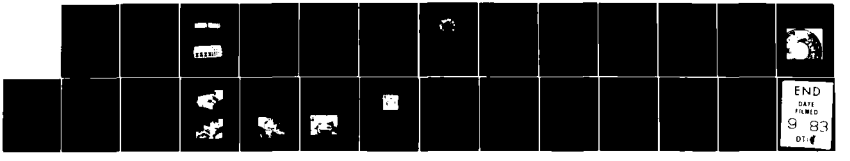
TABLE 36. EPOXIES USED FOR CHIP MOUNTING

Material	Type	Curing temperature °C	Curing time (minutes)
Ablebond 36-2	Conductive	125	60
Ablebond 41-5	Dielectric	125	60
Dupont 8762	Dielectric	160	120
		200*	120
Dupont 5504	Conductive	160	60
		200*	120

* Two-step curing process

AD-A132 514 MM&T--CERAMIC METAL SUBSTRATES FOR HYBRID ELECTRONICS (U) WESTINGHOUSE DEFENSE AND ELECTRONICS CENTER BALTIMORE MD A B TIMBERLAKE ET AL. AUG 83 2/2

UNCLASSIFIED HDL-CR-83-076-1 DAAK21-80-G-0076 F/G 19/1 NL



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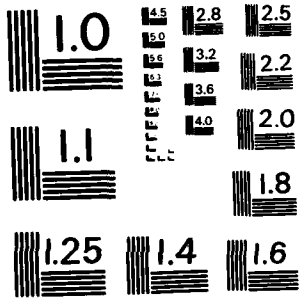

4.6.3 Testing and Results

The test pattern in Figure 57 was designed for use in the packaging evaluation. Pads were spaced in such a way as to accommodate both the semiconductor chips and the various styles of capacitor chips used on the M734 fuze amplifier.

Test patterns were printed on each of the types of substrate being used, with DP 7711 Pd-Ag.

4.6.3.1 Epoxy Chip Mounting

Integrated circuit chips were attached to substrates from each vendor using epoxies and cure cycles shown in table 36.

After epoxy curing, half the chips on each substrate were removed by a motor-driven push-off apparatus with a built-in force gauge. The forces required to remove chips ranged from 2 to more than 5 kg; in many cases the chip was destroyed before removal. In every case, the break was in the epoxy. No significant differences could be attributed to epoxy or substrate.

All substrates were subjected to the environmental stress cycle described in table 35. At the conclusion of the cycle the push-off tests were repeated. The same result was obtained, indicating that the epoxy bond on porcelain enameled substrates was not degraded by the stress. In addition, there were no instances of chip or substrate failure in the 10,000 g centrifuge.

4.6.3.2 Solder Mounted Capacitors

Two very different capacitor constructions were of interest in this program phase--ceramic chips, and large tantalum "dominoes." Figure 58 shows a substrate with both types of capacitor soldered in place. The procedure was to screen solder paste onto the pads, place the parts into the proper positions on the substrate, and reflow on a two-stage rotary reflow apparatus. Soldering temperature at the hot stage was 230 $\pm$ 5°C.

Push off tests before environmental stress resulted in frequent chip breakage at forces in excess of 5 kg. Substrates were then subjected to an environmental stress, followed by centrifuge to 10,000 g's. Substrates were held in a fixture designed for the purpose.

When mounted in the fixture the substrates faced away from the center of rotation. In this way centrifugal forces would act on the components in such a direction as to force them away from the substrate.

The ceramic capacitors survived the centrifuge testing. However, in the first run at 10,000 g, all four tantalum capacitors on a GE substrate and three of four on a PL low-carbon steel substrate came apart. These failures were in the capacitor body.

Cracks were observed in the tantalum capacitors in the plastic near the metal contact. Table 37 relates the incidence of cracks on the various substrates.

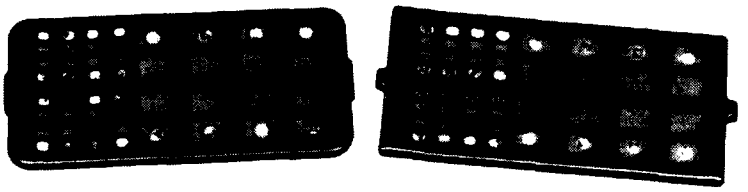

Figure 57. Test pattern used for packaging evaluations, epoxy-mounted chips.

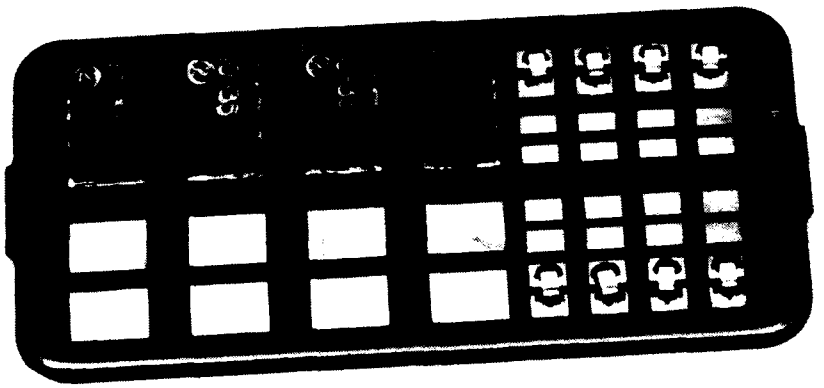

Figure 58. Test pattern with solder-mounted capacitors

TABLE 37. CRACKING OF TANTALUM CAPACITORS

Type	number of cracked capacitors
Stressed substrates	
ECA-1	0
ECA-2	1
GE-1	3
GE-2	1
PL-stainless	
Steel	0
PL-low carbon	
Steel	2
Unstressed substrates	
ECA-3	0
ECA-4	0
GE-3	0
PL-Invar	1

Time did not permit further investigation of the capacitor cracking. It appears that a thermal expansion mismatch between the capacitors and the substrates could be the cause of the problem.

4.6.4 M734 Mock-Up Assembly

Five mock up M734 fuse amplifiers were built in the thick film process. ECA substrates (2 x 2 in.) were used. ESL 9694 palladium silver was used as the solderable conductor, and TFS 3045 gold was used for wirebonding areas. The purpose of this operation was to ensure that a PES-based hybrid substrate was compatible with the processing operations required for assembly.

The first operation in assembly was attachment of solderable components. Substrates were screened with solder paste. In the first trial, the paste was dried, the capacitor pads were wet with flux and put into the paste. In a second trial, capacitors were put directly in the wet paste. Both procedures gave the same results. It was noted in solder reflow that blistering of the tantalum capacitors occurred with the reflow temperature at above 230°C.

Solder attachment of capacitors was followed by epoxy mounting of chips and wirebonding of chips. Although temperature cycling of these units had been planned, it was necessary to forego this step.

The five mock-ups were completed without exceptional problems.

4.6.5 Advanced Concepts

As a part of the packaging evaluation, a small effort was directed toward evaluation of insulated metal substrates using construction other than porcelain on metal. It was felt that several advantages would follow from this concept providing desirable physical and mechanical properties, and a surface on which to print thick-film circuitry using conventional ink. For example, the core metal could be chosen to have desired properties such as low thermal expansion coefficient, and a wider range of properties for thick film fabrication would be available if conventional high temperature inks could be used.

The Westinghouse R&D Center, Pittsburgh, PA, has investigated several candidate constructions for another DoD program which illustrate these concepts. Table 38 lists the core metals, coatings, and methods of application used for each coating. Several samples which were successfully coated were given preliminary evaluations. A porcelain enamel, EK5-EK6, spray coated on 1 x 2 in. pieces of Alloy 42 (a low expansion nickel-iron alloy), were able to withstand printing and firing of one dielectric layer and one conductor layer fired at 925°C. Properties of the conductor, DuPont 9791 gold, were similar to the properties obtained when firing on alumina.

TABLE 38. INSULATED METAL SUBSTRATE CANDIDATES

Core Metals	Coatings	Composite	Method of application
430 stainless steel	EK5/EK6[a]	Porcelain enamel	Spray
Alloy 42 (Ni-Fe)	334F	TiO_2 - Al_2O_3 - SiO_3 powder	Plasma spray
Copper-Clad Invar	105 SF[c]	Al_2O_3 powder	Plasma spray
Molybdenum	Linde A[d]	Al_2O_3 powder	Plasma spray

[a] Ferro Corporation
One Erieview Plaza
Cleveland, Ohio 44114

[b] Plasmadye Division of Geotel, Inc.
3839 South Main Street, P.O. Box 1559
Santa Ana, California 92702

[c] Metco Incorporated
1101 Prospect Avenue
Westbury, L.I., New York 11590

[d] Linde Division
Union Carbide Corporation
270 Park Avenue
New York City, New York 10017

Several substrates made by spraying the ceramic powders on Alloy 42 were also printed with thick film dielectrics and conductors and fired at 925°C. All gave good results in wirebonding tests. In general, these constructions showed promise, but are in need of considerable development.

A substrate construction which seemed to have desirable features was one consisting of very thin sheets of tape cast alumina bonded by solder glass to alloy 42. It was planned to bond plates of tape-cast 95-% Al_2O_3 purchased from Coors Porcelain of metal plates. The first bonding material was a porcelain frit mixture, EK5/EK6, which fuses at 1000°C. Attempts were made to bond the alumina using the porcelain at 1010°C to Alloy 42 and copper-clad Invar, (a laminate with an expansion coefficient matching that of alumina). These attempts were unsuccessful, as the bonding enamel (EKS/EK6) cracked during cooling.

Successful laminates of alumina (Al_2O_3) and Alloy 42 were fabricated by using Corning 7570 lead solder glass, which softens at 440°C.

It was not possible to evaluate these laminates as thick film substrates. One was fired in a thick film furnace at 850°C and survived, although the edges of the ceramic turned yellow.

5. PRODUCTION VERIFICATION

As a final step in the program, the experience gained in the several tasks was applied to manufacturing an ordnance hybrid now manufactured on ceramic. A small production run was planned, using substrates, thick film materials, processes, and design guidelines established previously. This production run would help to establish that insulated metal--specifically PES--substrates could be used with the processes we have detailed for large-scale production. This section discusses the production phase of the program.

5.1 VERIFICATION MODEL HYBRID

The circuit selected as the model for the production run was the M734 hybrid fuze amplifier. A version of this circuit made on ceramic is shown in figure 59. The assembly encompasses a wide variety of hybrid features, including

- o CMOS integrated circuits,
- o transistor and diode chips,
- o ceramic capacitors,
- o tantalum capacitors,
- o 21 thick film resistors - 3 decades,
- o static and dynamic resistor trimming,
- o 10 mil lines and spaces,
- o dielectric crossovers, and
- o solder printing.

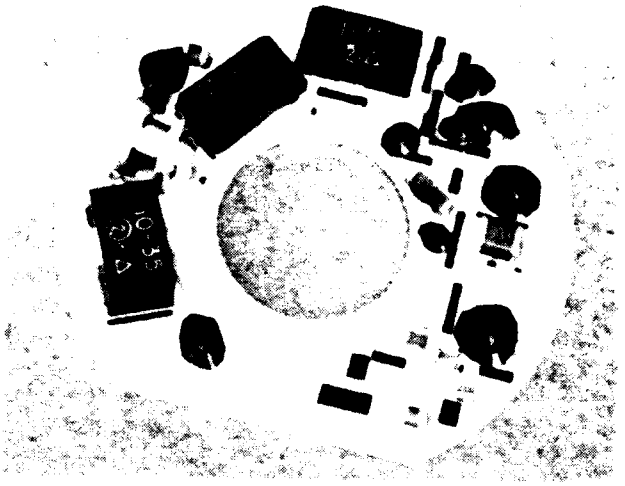

Figure 59. M734 hybrid fuze amplifier on ceramic substrate

Thus, the amplifier uses most aspects of hybrid fabrication technology, making it an excellent model for demonstration of technology adaptation.

5.2 THICK FILM FABRICATION

The M734 fuze amplifier represents an excellent proving ground for the thick film fabrication portion of the pilot line portion of the investigation. Most of the design features found on nonmultilayer substrate styles are found in the thick film layout, including

- o solderable and gold wire bondable conductors,
- o dielectric crossover patches with conductor crossovers,
- o resistor values requiring 3 decade sheet resistivity values, including one value blended in house,
- o both static and dynamic resistor trimming, and
- o solder printing and reflow.

With conductor and dielectric overprinting, 10 thick film layers (including solder) must be applied and at least 4 firing operations are required. Conductor layout density is typical of avionic circuits in current production on alumina. The circuit provides a measure of the potential of the technology for mainstream military hybrid production.

5.2.1 Substrate Selection

The substrates selected for pilot production were 2x2 in. PES from ECA. Two hundred substrates were ordered: 175 coated with conventional porcelain, and 25 coated with EL-POR II (TM--Ferro Corporation). Core material was conventional porcelainizing steel. It was specified that the cores be etched before enameling. All parts were coated on both sides using electrophoretic deposition.

The fuze amplifier was built on a 2x2 in. substrate rather than the 1.41 in. circular substrate, even though all artwork was based on the circular design. It was felt that the circular design would be much more expensive on a small purchase, and would not contribute significantly to the validity of results.

ECA was chosen as a vendor because, of the three vendors used in the substrate evaluation task, only ECA was still actively marketing the materials. Etching was specified, with ECA's concurrence, to round the edges and therefore reduce meniscus. Although EL-POR II appeared to offer advantages over the enamels previously used, it was felt that the pilot production should be made on a material previously evaluated.

5.2.2 Thick Film Inks Basis For Selection

Based on the circuit requirements and the results of the technology investigation, the following materials were required for thick film fabrication:

- o lead-tin solderable conductor paste,
- o gold-based conductor paste for wirebonding with gold wire,
- o unfritted, 100-% gold solids, gold conductor paste for overprinting wirebond sites,
- o crossover dielectric paste, and
- o 100 k, 10 k and 2 k ohm/sq resistor pastes.

The selection of the material used for pilot line production verification was based on two fundamental criteria:

- o the ability to fabricate circuit elements that performed their design electrical and mechanical functions reliably
- o the capability for use in high-volume production with minimum cycle times, broad process capabilities, and maximum yields.

Discussion of each material type highlights the critical measured properties for the attainment of the above criteria.

5.2.2.1 Conductors

Wire bondability.--The wire bonding tests performed as described in section 4 of this report indicated that the TFS 3045 overprinted with an unfluxed gold, Cermalloy 4300 UF, would meet minimum standards of wire bondability for production. A second material, Cermalloy EMD C5800, had performed well in limited tests, and was considered an acceptable option.

Solderability --The five alloyed silver materials discussed earlier were evaluated on the basis of the following four criteria:

1. wetting by Sn63-Pb36-Ag[2] solder,
2. resistance to leaching by the same solders,
3. adhesion in pull tests, and
4. adhesion in pull tests after aging at elevated temperature.

Detailed data were presented in section 4 of this report. On the basis of the test, DuPont 7712 and ESL 9694 were rated approximately equal. The TFS 3418 was very good in solder wetting and leach resistance, but ranked lowest in adhesion. The ESL 9694 was selected for production, since its superior wetting and leach resistance properties were considered necessary for high-volume production.

5.2.2.2 Resistors

Inks from each vendor in the ranges from 1 kohm/sq to 1 Mohm/sq were rated for use in fuze amplifier production on the basis of the following criteria:

1. nearness to nominal value, as-fired,
2. standard deviation around the mean value for given geometry,
3. drift of trimmed and untrimmed resistors over 800 hours at 150°C,
4. sensitivity of sheet resistivity to resistor geometry, and
5. sensitivity of sheet resistivity to firing temperature.

The evaluation did not produce a clearly superior system among the three vendors. ESL resistor inks ranked highest in nearness to as-fired value, and exhibited the lowest spread about the mean values, for each batch. In addition, they showed minimum sensitivity to geometry. All of these characteristics were considered desirable for achieving high-volume production. Also, an ESL solderable conductor had been selected as the solderable conductor, which also served as the resistor termination. Therefore, the ESL line of resistor materials was selected for use in the M734 fuze amplifier production.

5.2.2.3 Dielectrics

After a review of dielectric testing results, the need to produce pinhole-free crossovers was considered most critical. The EMCA 9041-1 showed slightly better performance than the TFS 1129CTG in this area, however; the EMCA material, fabricated under the test conditions, produced unacceptable interlayer adhesion. On this basis the TFS 1129CTG was selected for pilot production.

5.2.3 Results

5.2.3.1 First Batch

Using the optimum processing conditions, the PES substrate and thick-film characteristics, as reported in section 4, a process was laid out for the pilot line circuit. As no differences in layout requirements (geometry) were found between thick film processing on PES and alumina, the M734 layout was reviewed using existing Westinghouse design guidelines. The layout as designed was found acceptable for routine fabrication, which was not suprising, since this circuit has been produced in volume on alumina.

Next a standard instruction sheet (SIS) for thick film fabrication was written, giving material processing order and printing and firing conditions. This SIS is shown in figure 60. The materials were selected as described in section 5.2.2. The processing parameters shown on the SIS were designed to duplicate the optimum processing conditions found for each material during the thick film materials study. Care was taken to deal with the two difficulties noted with the thick film materials: wire bonding to conductors on PES and hermeticity of dielectrics. Three printings of different materials were used for the wirebonding regions of the substrate: base solderable conductor (Pd/Ag), fluxed gold, and unfritted gold. Since the existing artwork was not designed for this three-layer system, the wirebondable conductor layer also contained the crossover conductors, requiring that the dielectric layers and the first crossover conductor layer be fired before the resistors were printed. While the resulting topography was not ideal for resistor printing, a subsequent layout of the artwork for this purpose was not justified.

Using the SIS shown in figure 60, a 100 piece batch was started, using 2 in. x 2 in. substrates. One hundred twenty-five ECA substrates were selected from a single 1000-piece lot. A sample of 25 substrates was selected at random; thickness, camber and flatness were measured and compared to the results of the substrate evaluations, giving an acceptable quality level of 1.0. The entire 125-piece batch was then examined at 7X for blisters and chipouts. No substrates were eliminated for this reason. One hundred substrates were then selected at random for fabrication. First, the tabs on each substrate were filed lightly using a flat file to remove burrs that result from the shearing operation. Such burrs could tear screens during printing and, while they are easily removed, add processing that could be detrimental to a high-volume operation.

After deburring, substrate fabrication followed the SIS. Processing was routine, and results and cycle times for each process were well within normal behavior for similar substrates printed on alumina, with two exceptions. The fired thickness of the first conductor layer was 1.2 to 1.4 mils compared to 0.5 to 0.8 mil for similar materials printed under the same conditions and fired at 850°C for use on alumina. Probable causes include reduced sintering of the conductor at the lower PES firing temperature and the formation of palladium oxidation during firing. Palladium metal forms an oxide at temperatures above 300°, but the oxide decomposes at temperatures above 700°C. Since typical thick-film firing on alumina is done at 850°C, rapid cooling through the range of oxide formation minimizes oxidation.

Thick Film Standard Instruction Sheet

Drawing Number:	M734	S.I.S. Number:	1
Drawing Revision:	D	Origination Date:	4/14/83
Projects:	IMSMMT	Released With Batch:	1
Substrate Drawing:	ECA Rev:	Manufacturer:	
Blank Drawing:		Made From:	

Layer Number	C1-1	D1-21	D1-2B	C2-3	R105-4	R014-5
Layer Revision:	D	D	D	D	D	D
Special Instructions:	1					
Screen:						
Size:	5x5	5x5	5x5	5x5	5x5	5x5
Mesh:	325	250	250	325	325	325
Emulsion:	1.1	.5	.5	.5	.5	.5
Print/Roller Coat:						
Paste Type:	C9694	D1129	D1129	C3045	R3116	R3115
Durometer:	60	80	80	80	80	80
Length:	2.5	2.5	2.5	2.5	2.5	2.5
Pressure/Blade Gap:	5	5	5	5	5	5
Speed:	3	3	3	3	3	3
Breakaway/Clearance:	20	20	20	20	20	20
Mode/Applic. Method:	SP	SP	SP	SP	DP	DP
Drying Temperature:	150	150	150	150	150	150
Firing Profile:	650C	650C	650C	650C	-	-
Layer Functions:	SP ML	CR	CR	TL LR	LR	

Special Instructions: 1. File Tabs Before Printing

Layer Number:	R202-6	C2-3B
Layer Revision:	D	D
Special Instructions:		
Screen:		
Size:	5x5	5x5
Mesh:	325	325
Emulsion:	.5	.5
Print/Roller Coat:		
Paste Type	Blend	C4300UF
Durometer:	80	60
Lenght:	2.5	2.5
Pressure/Blade Gap:	5	5
Speed:	3	3
Breakaway/Clearance:	20	20
Mode/Applic. Method:	DP	SP
Drying Temperature:	150	150
Firing Profile:	-	625C
Layer Functions:		WBT WP TL L

Figure 60. Standard instruction shee (SIS) for first pilot line batch

However, PES peak firing temperatures are within the oxide formation range,but below the decomposition temperature, so oxidation during firing was increased. This fired thickness increase manifests itself in difficulties relating to resistor printing.

The second example of unusual behavior occurred during resistor printing. Excessive resistor spreading was noted between the terminations. This spreading was as great as 40 mils on some resistors and is shown in figure 61. This spreading increased fabrication cycle time in two ways. First, in some areas, the extent of the spreading was great enough to cause shorting to adjacent conductor tracks, requiring hand scribing. Obviously, such hand operations would be extremely detrimental in high-volume production. Also, during laser trimming, inconsistencies in resistor width made trimming in automatic mode (where kerf placement is a programmed function) impossible. Manual operation requires far greater cycle time and limits process control over kerf location, which could be critical on resistors that are later dynamically trimmed.

Resistor spreading is believed to have been caused by two factors. The increased conductor thickness made proper screen gasketing during resistor processing impossible, allowing for spreading, especially at the terminations. Also, low resistor paste viscosity at low shear rates increased resistor spreading after printing. These effects were not noticed during the technology assessment portion of the program because the conductor selected for the pilot line was not the one used for resistor sample termination. For the pilot operation, new lots of resistor materials were obtained, and the lot-to-lot differences in low-shear viscosity contributed to the observed spreading.

After fabrication resistors were trimmed to value using the system described in section 4.4.3 for laser setup. After trimming conditions were determined, the batch was trimmed without incident. Kerfs were placed manually because of the resistor spreading discussed earlier.

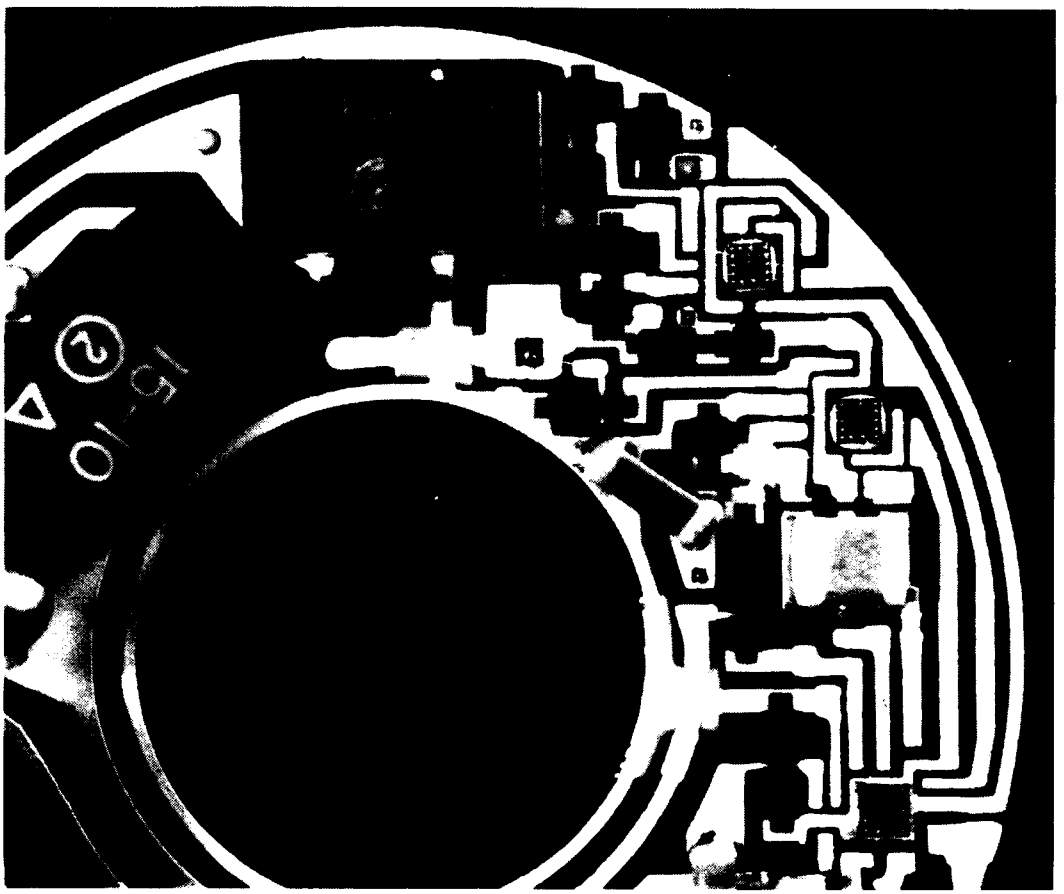

Figure 61. Close-up of fuse amplifier circuit showing degree of resistor spreading.

5.2.3.2 Yield

Yield for the pilot line production was measured by noting the number of resistor setups that were required and by the fraction of substrates completing fabrication and trim.

In a custom, small-batch process, as was used for the pilot line, resistor processing is best facilitated by producing a single set-up piece with each resistor paste and measuring each resistance. If the values are within a range that can be trimmed without violating minimum trimmed width criteria, then, the batch of parts is processed using the same screen printer setup parameters. If values are outside this trimmable range, setup parameters are altered and the setup process is repeated. During the pilot line run, two of the resistor layers required a single setup, and the third required two. This compared favorably with the setup efficiency of production line parts fabricated on alumina.

With 100 pieces beginning the print run, 93 were fabricated successfully and were available for trimming. The seven pieces lost were used for resistor setup or were rejected for excessive resistor spreading. Eighteen additional pieces were lost during trimming due to resistance values higher than tolerance before trimming. The overall yield of 75 percent is typical of first prototype batches of circuits of comparable complexity, fabricated using traditional thick film materials on alumina.

5.2.4 Second Batch

After evaluating the results of the first pilot line batch, changes were made in processing to demonstrate that the significant yield detractor found in the first batch, resistor spreading, could be eliminated. Also, changes were made to enhance manufacturability and process yield. The following changes were made:

- The solderable conductor screen emulsion thickness was reduced from .0011 to .0005 in. This reduced resistor termination thickness from .0014 in to .0009 in., facilatating gasketing during resistor printing.

- In order to insure sufficient solder leach resistance, a second printing of the solderable conductor was made using the artwork designed for solder paste printing. This layer was the last layer printed and was fired with the resistors and the unfluxed gold.

- The second dielectric layer was cofired with the crossover conductor layer.

- The same lots of resistor paste used for the technology evaluation was used. It was felt that the second lots showed excessive secondary flow.

- Conductor and dielectric firing temperatures were lowered from 650° C to 625°C.

Using this revised processing a second batch of circuits was fabricated up to, but not including, laser trimming. Processing was routine, as in the first batch, and resistor spreading was reduced from up to 0.040 in. to 0.005 in. or less.

5.3 ASSEMBLY OPERATIONS

The final step in the program was assembly of working hybrids. The purpose was to demonstrate that the soldering, epoxy chip mounting, and wirebonding processes developed in the earlier tasks could be applied in a production environment.

A process flow diagram is shown in figure 62. Details of each operation are given in the following sections.

The number of parts processed was relatively small, and the assembly operations were manual. Nevertheless, an effort was made to simulate high-volume conditions where automatic equipment would be used. For example, wire bonding pads and solder pads were not burnished, since this step would be avoided in production. Thermosonic wire bonding was used, even though earlier data showed thermocompression bonding to be advantageous. Finally, ceramic capacitors were not pre-tinned since many models of automatic placement equipment do not function well with pre-tinned parts. As a result of these decisions, assembly was more difficult than might have been necessary for a small lot. However, a better insight was gained into the problems that might occur in truly large volume production.

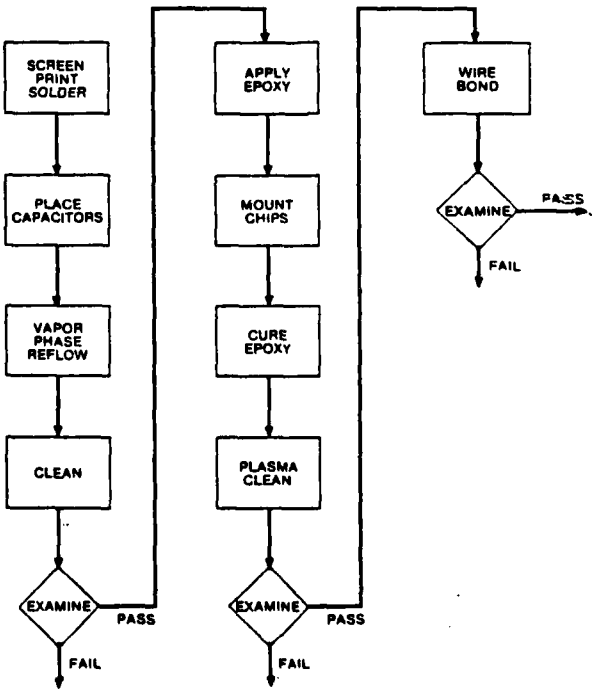

Figure 62. Process flow diagram.

5.3.1 Component Attachment

Components are attached to the substrate using both soldering and epoxy. The soldering operations were done first since they required the highest temperatures. Active device chips were mounted using conductive epoxy. The final step was to bond gold wires from the chips to the substrates.

The 75 substrates received in the first run were divided into groups of 25. Only the first group of 25 was completely assembled.

5.3.1.1 Component Soldering

Since all solder pads on the substrate were Pd-Ag, Sn62 solder, (2% Ag), was used to retard leaching. A commercial paste with RMA flux containing 85-percent solids was used.

Solder was applied in a screen printing operation shown in figure 63. An 80-mesh stainless steel screen with 3-mil emulsion was used.

It was found that two printings were necessary to achieve a satisfactory thickness of paste. After the second print, the paste was dried to tackiness, by baking for 15 minutes at 50°C.

All capacitors and the impact switch were manually positioned on the substrate in the tacky paste. Solder was reflowed in an automatic vapor phase system using a 3-s dwell. (The dwell time may vary for substrates of different sizes.)

After solder reflow, assemblies were cleaned in a commercial flux removal solvent, Alpha 564. Solder balls and other residue was easily removed since the components are relatively open. An inspection especially for solder balls was made at this time.

The solder attachment process was generally without problems that could be attributed to PES substrates. Wetting of solder pads was good, and cleaning was not a problem. It was found that the tantalum capacitors could blister in vapor phase soldering if the dwell time was too long. Also, ceramic capacitors of uncertain wetting characteristics could go undetected until assembly, since capacitors were not pre-tinned. However, no problems occurred in soldering that are not seen in the assembly of conventional hybrids on alumina substrates.

Figure 63. Screen printing solder.

5.3.1.2 Chip Mounting with Epoxy

After capacitor soldering, semiconductor chips were mounted using Ablebond 36-2 conductive epoxy. The chip placement equipment and procedure were the same as are used for conventional hybrids. As can be seen in figure 64, chips

Figure 64. Mounting chips on PES substrates.

were removed from a "waffle tray" with a turretted vacuum collet, and positioned on the substrate where a measured amount of epoxy had been deposited previously. Diagrams to aid identification, location, and orientation of chips can also be seen in the figure. The chip complement for each assembly consisted of three integrated circuits, three transistors, four diodes, and one bridge rectifier.

After chip mounting was complete, epoxy was cured for one hour at 125°C.

5.3.2 Wirebonding

Assemblies with chips mounted were then submitted for wirebonding.

Small groups, typically five, of assemblies were cleaned in argon plasma for 15 minutes.

Wirebonding was done on Mek-el Model 827 Thermosonic Bonders as shown in figure 65. Note again the diagrams used as an aid in placement of wirebonds.

Figure 65. Wirebonding to Chips on PES Substrates

Figure 66 shows in detail the substrate mounted on a heat column for wirebonding. (Note how high the tantalum capacitors and impact switch extend above the substrate, a hazard to rapidly moving capillaries and hydrogen flame-off torches.)

In spite of the extensive effort that had been devoted to establishing a satisfactory wirebonding process, including overprinting of wirebond pads with unfritted gold, wirebonding proved to be very difficult. Multiple attempts were required on many bonds. Stitch bonds had to be reinforced with ball bonds. Finally, it was necessary to use thermocompression bonding on two units in order to complete the assembly.

Because of limitations on time and funding it was not possible to solve the wirebonding problem. However, 10 substrates as shown in figure 67 were completed and delivered to Harry Diamond Laboratories for test. Fifteen substrates complete through the chip mount process wire also delivered. Finally, 50 substrates with trimmed resistors and 35 untrimmed substrates from the second thick film run were also delivered.

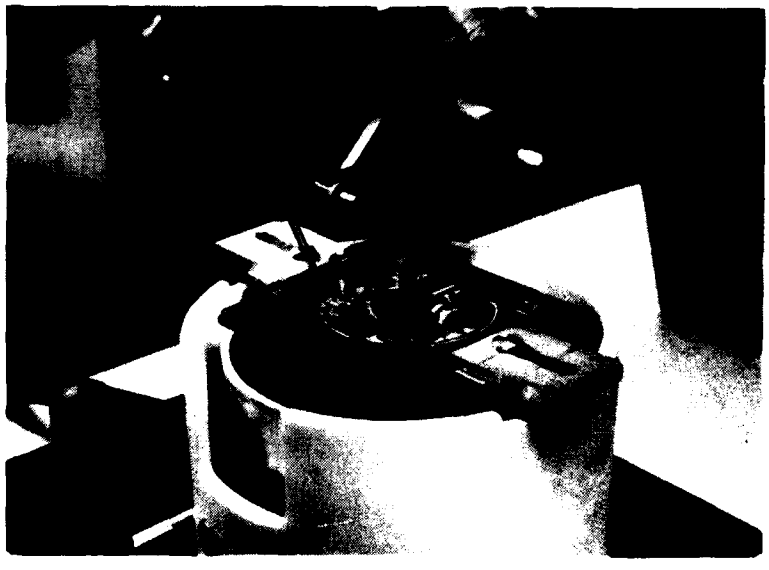

Figure 66. Closeup of Substrate Mounted for Wirebonding

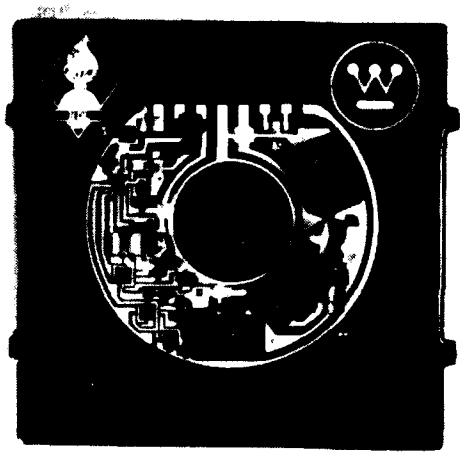

Figure 67. Completed M734 fuze amplifier assembly.

5.3.3 Electrical Testing

Although electrical testing of the completed amplifiers was not part of Westinghouse task, the results of tests are considered relevant and are reported here. In the facility at Harry Diamond Laboratories, the following tests were performed on completed units: bridge current, oscillator B+, reset-timer, arming time, and disable voltage. The PES-based fuze amplifier performance in these tests was identical to that of alumina-based amplifiers.

5.4 DISCUSSION OF PRODUCTION EXPERIENCE

5.4.1 Thick Film Production

Two production runs of the M734 fuze amplifier on PES substrates were accomplished efficiently, with minimal amounts of touch-up and re-work required. In addition, hundreds of test substrates, many of them requiring two or three printings, were also printed and fired without major difficulty. The most serious problem in thick film production was the spreading of resistor prints, which made laser trimming difficult. This problem was reduced substantially in the second run by reducing conductor thickness. It is possible that

palladium-silver conductors should be avoided when firing in the 600 to 650°C range, because of the oxidation of palladium at these temperatures.

The topography of the PES substrate surfaces and features such as meniscus were not a factor. The uniformity of print from one substrate to another was also very good.

5.4.2 Assembly

As was the case in thick film operations, PES substrates usually did not require substantial changes of procedure for successful assembly. An exception must be made, of course, in discussing wire bonding. Since the wirebonding difficulty occurred at such a late date in the program, it was not possible to try several alternate approaches to making the bonds. These could have included use of a heated capillary, use of a harder (or softer) wire, different thick film firing profile, and different conductor ink. Inasmuch as it had been possible to have a satisfactory wirebonding process in the earlier phase of the program, it seems entirely probable that a satisfactory solution exists for the assembly operation.

6. CONCLUSIONS

At the end of the technical phase of the program, large amounts of data had been acquired on numerous properties of PES substrates and on the characteristics of PES substrates in a thick film hybrid production environment. A principal objective of the program was to detail the methods and technology needed to achieve high-volume production using PES substrates on a thick film hybrid now made on alumina substrates. In concluding we will attempt to determine how we stand with regard to that objective.

Several "scenarios" on the achievement of high-volume production are possible, depending on the uniformity of vendor-supplied parts and materials, compatibility of designs with parts and materials, and permissible tolerances of parts properties for use with given processes and designs. For example, suppose that a certain manufacturing process can be used only with parts for which a certain property falls within very narrow limits, say one percent of the mean value. Suppose further that in a typical manufacturing lot of that part the property of concern falls within a range 10 percent above and below the mean. Obviously, a sorting or screening operation must be interjected in order for satisfactory parts to be provided for the manufacturing process. Thus, manufacturing cost increases. Furthermore, the cost of parts increases because 10 times as many as needed must be manufactured. The opposite extreme, in the manufacturing sense, is the case where vendor-supplied parts fall within a very narrow range about the mean value, but the manufacturing process is able to accept parts falling in a very wide range. In this case one would look for ways to improve the design, automate the process, or increase the part manufacturing rate.

Which of these situations is the better approximation when considering the manufacture of a complex thick film hybrid on a porcelain-enamelled steel substrate? In attempting to answer this question it should be beneficial to divide the assembly into its separate elements, as was done in conducting this program.

Substrates.--A thick film hybrid substrate, whatever its other properties, must meet minimum conditions of flatness and surface smoothness. Close tolerances must be met on length, width, and thickness. The insulating coating must be thick enough and free of pinholes to isolate the metal core from the substrate. These are fundamental requirements. Our data indicate that vendors are able to supply substrates which meet these requirements, with two qualifications. First, substrate flatness should be very carefully specified. Second, for certain applications, it may be necessary to discuss with the vendor techniques for reducing the size of the edge meniscus. The coatings on all substrates used in the thick-film and product verification phases were uniformly excellent--free of pinholes, chipouts, blisters, and other defects.

Thick Film.--After a film is printed, it must be fired in a temperature schedule that promotes various characteristics in the film. In this process, an interaction occurs between the film and the substrate, the extent of which must be controlled enough to permit beneficial effects, such as adhesion, but minimize deleterious effects, such as glassy, non-solderable film surfaces. Substrates evaluated in this program softened at approximately 600°C, and interacted deleteriously with fired films above 625°C. Most thick film inks formulated for PES substrates are said to achieve optimum properties in the 600 to 650°C range. Thus, there may be a very narrow temperature window in which satisfactory films properties can be obtained.

It should be noted that no obviously deleterious interactions between the substrate and the thick film were seen at any firing temperature. That is, there were no blisters, "brown plague", "floating" patterns, or other undesirable conditions which are readily visible. However, films fired at 650° or 675°C had a very different appearance from those fired at lower temperatures and were generally not as solderable. In addition, the most stable resistors were those fired at 600°C. Conductor films fired at 575°C were exceptionally adherent and conductive, and could be used for many applications. However, their strength in solder peel was relatively low.

Assembly.--In assembly, all operations except wirebonding were similar in execution to the same operations on conventional substrates. Chip-mounting, epoxy bonding, solder application, solder reflow, and cleaning were all performed using standard procedures. In wirebonding, a process always requiring the utmost care, a solution which worked for test pieces did not work for a production run. Although the reason for this particular failure is not known, it was shown that wire bonding to a film was improved by increasing the gold-to-glass ratio, and by increasing the film sintering. These changes would require development effort by both the substrate vendor and the thick film ink vendor.

In the program just completed, it was shown that a thick film hybrid could be processed through most operations in high volume with acceptable efficiency. Only in wirebonding is there a serious question as to the applicability of PES substrates to a single-layer hybrid. Several approaches were shown to be effective in improving wirebondability, and could be carried further. Denser gold films and substrates with higher firing temperatures should lead to improvement. Several features of the wirebonding process itself, such as hardness of the wire, shape of the capillary, and temperature of the capillary, could be optimized.

Finally, if wire bondability cannot be improved sufficiently, another chip packaging technology could be explored. An approach which appears to be within the current state of the art would be to mount the chips in leadless ceramic chip carriers. A porcelain-enameled, copper-clad Invar substrate could be used for interconnecting circuitry, with the chip carriers soldered in place. It is recognized that there may be other trade-offs in this approach which must be considered.

In closing, it has been demonstrated that porcelain-enameled steel substrates of consistently high quality are available on the open market. Manufacturing processes for thick film hybrids using the substrates have been detailed. Areas whose further development would be desirable have been emphasized.

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